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1966

TECHNICAL MEMORANDUM

ESL-TM-228

AN APPROACH TO COMPUTER-AIDED PRELIMINARY SHIP DESIGN

by

Mackenzie L. Hamilton

and

Abbott D. Weiss

January, 1965

Contract Nos. AF-33(657)-10954
and NoBS 90100

Electronic Systems Laboratory

MASSACHUSETTS INSTITUTE OF TECHNOLOGY, CAMBRIDGE 39, MASSACHUSETTS

Department of Electrical Engineering

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The work reported in this document has been made possible through the joint support and sponsorship extended to the Massachusetts Institute of Technology, Department of Naval Architecture and Marine Engineering, by the Department of the Navy, Bureau of Ships, under Contract NoBS 90100 (M.I.T. Project DSR 9971), and to the M.I.T. Electronic Systems Laboratory and the Mechanical Engineering Department by the Manufacturing Technology Laboratory, RTD, Wright-Patterson Air Force Base, under Contract AF-33(657)-10954 (M.I.T. Project DSR 9442). It is published for technical information only and does not necessarily represent recommendations or conclusions of the sponsoring agencies.

Work reported herein was supported, through access to its computer facilities, by Project MAC, an M.I.T. research program sponsored by the Advanced Research Projects Agency, Department of Defense, under Office of Naval Research Contract Number NOnr-4102(01).

Approved by: Douglas T. Ross
Douglas T. Ross, Project Engineer
Head, Computer Applications Group

Electronic Systems Laboratory
Department of Electrical Engineering
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

NOTICES

ABSTRACT

This report describes an application of Computer-Aided Design concepts to the general preliminary design of ships, in which shape description plays an important part. Although the present study is preliminary in nature and will require considerable elaboration for practical use, it does indicate the feasibility of the approach.

The design and evaluation of hull forms was accomplished "on line" using the Project MAC time-shared digital computer, the display console developed by the MIT Electronic Systems Laboratory, and a very general, parametric surface description technique developed by Professor S. A. Coons. Three-dimensional hull surfaces displayed on the CRT screen could be altered in a few seconds by typed-in changes in parameters, and could be rotated to any desired viewing angle for study. Using these techniques, the lines of the US DD 692 were simulated such that the routines for calculating midships coefficient, prismatic coefficient, displacement, wetted surface area, and centers of buoyancy yielded values closely resembling those of the actual ship. A brief economic analysis shows the great saving in time and cost and the corresponding increase in study of alternative designs which would be possible with such a design system.

ACKNOWLEDGEMENT

This report is based on a joint thesis submitted to the Departments of Mechanical Engineering and Naval Architecture on August 22, 1964, in partial fulfillment of the requirements for the degrees of Master of Science. The autors express their gratitude to Professor Steven Coons of the Department of Mechanical Engineering and Professor Philip Mandel of the Department of Naval Architecture and Marine Engineering for having initiated and guided this project as the thesis supervisors. It was the combination of Professor Coons' enthusiasm and insight into the philosophies of the Computer-Aided Design Project and Professor Mandel's knowledge and interest in the naval ship design process which provided the foundation for the authors' work.

Second, the authors are greatly indebted to the members of the Mechanical Engineering Computer-Aided Design Group for their patient teaching of the mysteries of computer programming. Special thanks are due to Richard Parmelee, Tim Johnson, Charles Garman, and Coyt Tillman for their help.

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LIST OF SYMBOLS

Naval Architecture Terms

B	maximum beam in feet
B/H	beam-draft ratio
BM	distance in feet between center of buoyancy and metacenter
C_f	frictional resistance coefficient
C_p	prismatic coefficient
C_r	residuary resistance coefficient
C_s	wetted surface coefficient
C_t	total resistance coefficient
C_v	volumetric coefficient
C_x	midships coefficient
EHP	estimated horsepower
GM	distance between center of gravity and metacenter
H	draft in feet
KB	vertical center of buoyancy measured from baseline in feet
KG	vertical center of gravity measured from baseline in feet
L	length of ship at waterline in feet
LCB	longitudinal center of buoyancy
LCG	longitudinal center of gravity
P_s	installed horsepower
SHP	shaft horsepower

V_e	endurance speed in knots
V_s	sustained speed in knots
$V/\sqrt{L}$	speed-length ratio
W_f	fuel weight in tons
W_p	payload weight in tons
$\triangle$	displacement in tons
∇	displacement volume in feet^3

Other Symbols

A_{ij}	bicubic coefficients
A, B, C, D	arbitrary coefficients
A	surface area
dA	elemental surface area vector
dA_x, dA_y, dA_z	projected areas of surface element
dU	elementary vector with w = constant
dW	elementary vector with u = constant
E_n	endurance in miles
$F_0(\ )$, $F_1(\ )$	blending functions
F_t	force in lbs. in t direction
g	gravity in ft/sec^2

I_a, I_b, I_t	mass moments of inertia
I_{wp}	waterplane inertia
i	unit vector in x direction
j	unit vector in y direction
k	unit vector in z direction
J_x, J_y, J_z	Jacobians
m	mass in $lb\text{-}sec^2/ft$
M_t	moment about the t axis in lb-ft
N	indexing integer
p	pressure in lb/ft^2
R_e	Reynolds number
$R_{(x,y,z)}$	distributed load
dQ_{II}, dR_{II}, dS_I, dT_I	elemental unit vectors
s, t	dummy symbols for x, y, z
t_c	location of center of gravity
t	point of application of resultant

u, v, w	curvilinear coordinates
V	volume
WS	wetted surface
x_m	longitudinal position of maximum area
y_0	sectional area at the stern
y_1	sectional area at the bow
x, y, z	Cartesian coordinates
α, β, γ	storage registers
ρ	density in $lb\text{-}sec^2/ft^4$
$\times$	vector cross product

I. INTRODUCTION

A. HISTORY

The advent of the digital computer in modern technology has added greatly to man's capabilities. Computers have been applied to serve and assist men in all areas of science and engineering. One such area is design.

The Computer-Aided Design Project at M.I.T. began in 1960 as a joint endeavor of the Computer Applications Group of the Electronic Systems Laboratory and the Design Division of the Mechanical Engineering Department. Early efforts of the Project were concerned with establishing fundamental techniques which would lead to a man-machine system in which the designer and the computer can work intimately together as a team on design problems requiring creative solutions. Progress made by approaching the common goal from the computer applications and design viewpoints has led to a stage where beginning applications to actual design problems are feasible. This report represents the first application of Computer-Aided Design concepts in a realistic pilot study. Although simplified, the work reported here is indicative of the kind of man-machine interaction appropriate to the general class of preliminary design problems in which three-dimensional shape description plays an important part.

This study is concerned with the specific example of destroyer feasibility studies in the process of preliminary ship design. The work combines the efforts of the Computer-Aided Design Group in the M.I.T. Mechanical Engineering Department with those of the Department of Naval Architecture and Marine Engineering. This work will be continued and elaborated in the next few years, and the joint effort is a model for the kind of cooperative arrangements which the Computer-Aided Design Project hopes to establish in various design areas with other M.I.T. projects and with industry groups.

B. PHILOSOPHY

A combination of "man and machine in an intimate cooperative complex can use the creative and imaginative powers of the man and the analytical and computational powers of the machine with the greatest possible economy and efficiency."* This combination is the basis of the philosophy of Computer-

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* S. A. Coons, "An Outline of the Requirements for a Computer-Aided Design System," Proceedings of the Spring Joint Computer Conference (SJCC), 1963, p. 300.

Aided Design. Indeed, experience with computers has already shown that these "different powers of man and machine are complementary powers, cross-fertilizing powers, mutually reinforcing powers."*

To reap the maximum benefits from this combination, there must be fluent communication between man and machine. This is an important aspect of our computer-aided design system.

Because the designer often perceives the solution to his problem in graphical form, much effort has been directed toward development of techniques by which the designer and computer may communicate graphically. The principal hardware components of the man-machine system which have evolved from this effort are the display scope and the light pen. The display scope is an ordinary cathode ray tube which executes the user's commands by means of a pre-programmed computer. The light pen is a photosensitive device which responds to the light generated by an intensified point on the scope face. While the light pen is, in reality, a receiving device, it functions for the designer as a transmitting device which enables him to "draw" a sketch on the scope for the computer to understand much the same as a pencil is used to draw on paper for the man to comprehend the ideas in his mind.

Using the hardware of scope and pen with Sketchpad,** a sophisticated "drawing program", the designer can draw an object of interest on the scope; he can modify his sketch at will; he can erase a line with the flick of the pen; he can shrink or expand his sketch by turning a knob; and he can design a surface in space and rotate it on the screen as if he had the object in the palm of his hand. All this is possible whether the object be a 5000-ton ship or an 8-ounce tobacco pipe.

Thus, the light pen and scope, together with various knobs, switches, and buttons, and an input-output typewriter comprise the console utilized by the designer.

A closely related project at M.I.T. which has considerably enhanced the practical and economical aspects of this console is the concept of time-sharing

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* Loc. cit.

**T. E. Johnson, "Sketchpad III, A Computer Program for Drawing in Three Dimensions," Proceedings of the SJCC, pp. 347-353.

Also I. E. Sutherland, "Sketchpad, A Man-Machine Communication System," Proceedings of the SJCC, pp. 329-346.

currently under development at the M.I.T. Computation Center and Project MAC.* Each time-sharing system enables (at present) thirty people at remote individual typewriter consoles to employ a single computer simultaneously**. All of the programming in this study was done on Project MAC's IBM 7094 computer, using the ESL Display Console for the graphical work.

The primary purpose of a time-sharing system is maximum utilization of computer time -- which implies minimum time loss due to slow man-computer interaction. Use of the graphical input-output console allows the designer to pause and study his design at all stages in its process without unnecessarily tying up the computer. Furthermore, he can make modifications at any time and be appraised within seconds of the effects of each change.

It must be emphasized that the philosophy of Computer-Aided Design depends very much on the word "Aided." This is not "Automatic Design," a closed system of computer programs into which a set of requirements are dropped at one end and out of which a finished product appears at the other. Computer-Aided Design envisions a system in which a man -- a creative, resourceful, experienced, unpredictable human being -- forms a vital link in the loop. This concept brings out the second major aspect of our computer-aided preliminary design study, namely, the distinction between those parts of the process best done by the designer and those best suited to the capabilities of the machine.

In accomplishing the work described in this thesis, the authors were able to take advantage of the tools available; of time sharing, of graphical computer communication, of emergent sophisticated programming techniques, and of the backlog of experience available within the Design group. Using these tools, the authors have constructed a prototype system that will make it possible for the naval architect to carry out the preliminary design of ships in a natural, convenient, and very much faster way.

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* MAC is not a specific acronym. Two popular meanings are: Multiple Access Computer, and Machine-Aided Cognition.

** F. J. Corbato, and others, The Compatible Time-Sharing System, M.I.T. Press.

C. PERSPECTIVE ON PROGRESS

One of the major contributors to the Project said a year ago that "general three-dimensional graphical communication, which deals with arbitrary surfaces and space curve intersections, presents many difficult problems; the beginning has been modest and much work remains before the complete graphical communication problem is solved."* Within the past year progress has continued in dealing with problems of graphical communication, and many of the developments have been a filling-up and building upon the framework and foundation established by earlier work.

In much the same way, this thesis must be regarded as a beginning, certainly not as a finished product. The methods and processes described here outline the structure of computer-aided preliminary ship design as a specific model or prototype of any general design system. The first year's work on this project has been to establish the skeleton and to begin to attach meat to these bones. The job of continuing to add muscle to make this system a fully-functioning body must be accomplished by further research efforts on this project.

A parallel development toward which effort must be directed is the incorporation and assimilation of the results of these studies with others in man-machine communication, language development,** stress analysis, circuit analysis, etc., into the entirety of the Computer-Aided Design Project. To be truly useful in a functional environment the basic features of the system presented in this report must be augmented by further capabilities. In particular, the "built-in" processes must be capable of being altered during the design process, by the designer himself, so as to adapt the system to the vagaries of the problem at hand. Work toward these objectives is described in other Project reports.† ‡

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* Johnson, op. cit., p. 329

** D. T. Ross and J. E. Rodriquez, "Theoretical Foundations for the Computer-Aided Design System," Proceedings of the SJCC, pp. 305-322.

† AED Jr. May 6 Demonstration Memos

‡ C. A. Lang, R. B. Polansky, and D. T. Ross, "Some Experiments with an Algorithmic Graphical Language," M.I.T. report to be published.

II. PRELIMINARY DESIGN PROCESS

A. GENERAL

Design is the process in which man devises an object or system to satisfy a human need. Preliminary design is the first portion of that process, the portion in which the object or system is taken from its conception in the designer's mind to its description on paper in some combination of graphical, analytical, and numerical terms such that the primary requirements of the problem are satisfied.

The completion of the preliminary design stage is much more easily written about than accomplished, for the process is highly complex. In his efforts to reach a solution to his problem, the designer is faced with a large set of variables, some discrete and other continuous, some readily determinable within a narrow range and others elusive because of their wide variability, but all interrelated, or cross-coupled, with varying degrees of intricacy.

By nature, as well as number, these cross-couplings increase the complexity of the problem.

> "Some couplings are weak, some are strong. If the relationships happen to be linear, the cross-couplings are constant in strength, but usually the relationships are non-linear, and the mutual influences of the various variables change with their values.
>
> "The designer structures such relationships so that he can thread through them, taking advantage of the loose couplings where possible, to obtain hopefully an exact, but more usually a first, or second, or closer approximation to the values of the variables. It is not at all unusual for this structuring to be done graphically, in the form of block diagrams or linear graphs or information flow charts. Thus he uses a graphical form for both the topological and geometric description of the design, and also for its abstract description in terms of physical function." *

The above characteristics of the design problem strongly suggest that the process would be greatly enhanced if tools were made available by which the designer could be quickly appraised of the multifaceted effects of fixing any particular variable. Such is the capability of the high-speed digital computer. In the following section, the specific design problem of ship feasibility studies is discussed, and the areas adaptable to analysis by the computer are pointed out.

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* Coons, op. cit., pp. 300-301.

B. SHIP EXAMPLE

There are actually two phases of Preliminary Naval Ship Design:

a) Feasibility study - pre-characteristics phase

b) Actual preliminary design - post-characteristics phase

This report concentrates on the first phase, which is in most respects simply a rougher, less-detailed predecessor to the second.

A feasibility study is initiated in the Navy's Bureau of Ships at the request of the Ship Characteristics Board (SCB), who specify their needs essentially as follows:

1. Mission and Tasks
2. Payload (Armament, Communication and Control, Aircraft, etc.) - type, tons
3. Speeds (Sustained, endurance) - knots
4. Endurance (Range at endurance speed) - nautical miles at -- knots
5. Machinery Type (Conventional or Nuclear)
6. Complement - men

The solution reached by the naval architect at the end of a feasibility study is a proposed ship described by the following principal variables:

- Length
- Beam
- Draft
- C_p
- C_x
- Displacement
- Estimated Weights
- Speed - power curve
- Hull Shape (Body plan, rough lines Dwg.)
- General Arrangement
- Estimated Centers of Gravity
- Stability (GM)

Because of the complex interrelationships among these variables, the solution must be achieved by a trial-and-error iterative method, beginning with a set of hull dimensions and coefficients which the designer thinks might do the job on the basis of other recent designs. Figure 1 shows a "Design Spiral" describing the cyclical nature of the process. Different groupings and sequences

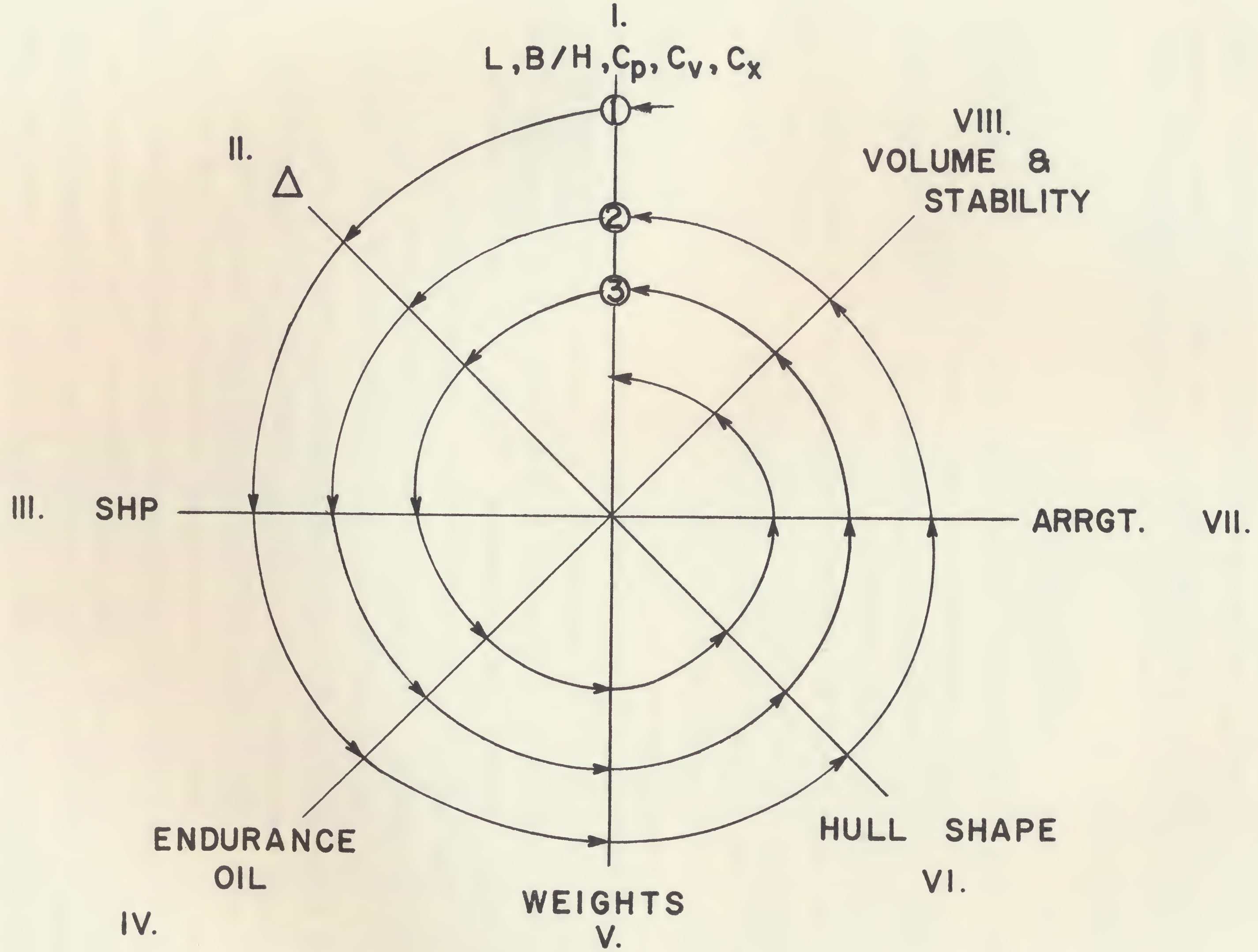

Fig. 1 The Design Spiral

are possible in any given spiral depending on what information is available, but the nature of the process remains unchanged.

To begin the cycle the designer examines the requirements set forth by the SCB, and he estimates several hull dimensions and parameters. This is shown at point 1 in the flow diagram, Fig. 2. The naval architect guesses a length, L, and a volumetric coefficient, C_v, as convenient parameters to fix a trial displacement, Δ :

$$\Delta = C_v \, L^3/35$$

At this initial point he also chooses a beam/draft ratio, B/H, and a prismatic coefficient, C_p,for powering estimates. A final input for resistance and powering is the wetted surface coefficient, C_s, which can be estimated from Saunders' * plot from the midship coefficient, C_x, and B/H.

Using these parameters the designer must estimate the horsepower needed to achieve the specified speeds. These calculations can be made using Taylor Standard Series resistance data and a standard frictional resistance line, with appropriate modifications for hull form, appendage resistance, service and roughness allowances, and propulsive efficiency. Such calculations are straightforward but time-consuming manually, so computer application is appropriate here. As an example, the authors have used an IBM 7094 computer to calculate 19 points (15 to 33 knots in 1 knot steps) on a speed-power curve. Calculation time was 2 seconds, and with the benefit of the time-sharing teletype, the answers were completely printed out in approximately 12 seconds. The same amount of work manually might well take an hour -- and the probability of errors would be considerably higher.

Knowing horsepowers and an estimated displaced weight of water, Δ (from L and C_v), the designer can estimate empirically the weights of the major items on his ship. Using a collection of previous designs for his estimates, ** he can sum all the weights and compare with his trial displacement, Δ. If these two are not close enough, he must change one or more of his initial parameters and recycle. This stage, known as "The Solution of the Weight Equation," is readily done iteratively by the combination of man and computer, as can be seen by looking at a weight equation for destroyer-type vessels:

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* H.E. Saunders, Hydrodynamics of Ship Design, Volume II.

** P.M. Mandel, Interim Report of Mathematical Model of Destroyer-Cruiser Design Problem, Institute for Naval Studies.

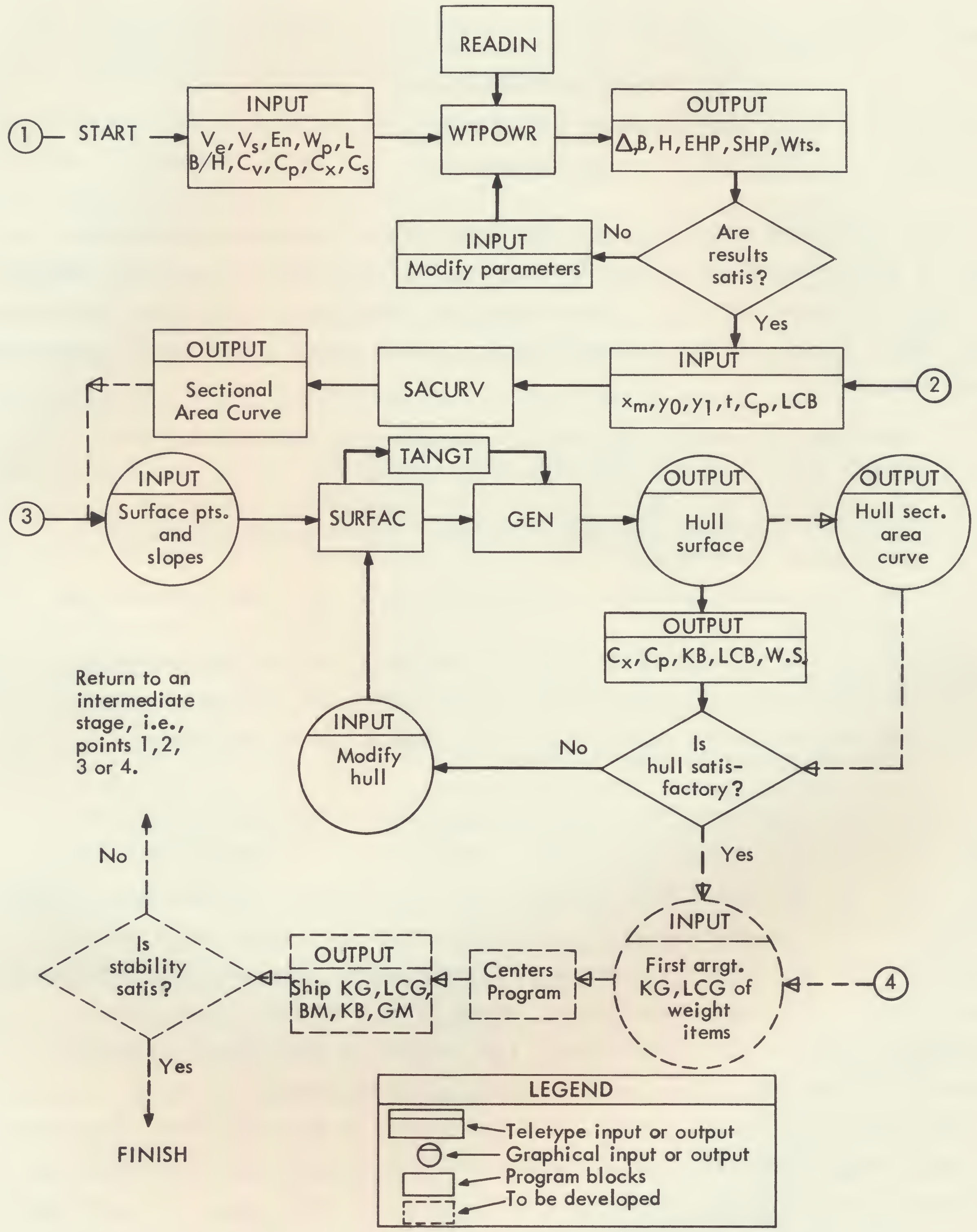

Fig. 2 Flow Diagram of Computer-Aided Ship Design Process

$$\Delta = .399\Delta + 1.58\Delta^{2/3} + .01376\ P_s + W_f + W_p$$

where

P_s = installed horsepower
W_p = weight of payload
W_f = weight of fuel

After sufficient recycling, the designer progresses to the hull form stage. A preliminary aid to hull description is a sectional area curve, which is a graph of cross-sectional areas below the waterline plotted over the length of the ship. There are six characteristics of this curve known to or estimated by the designer:

1. The total area under the curve normalized by the product of length and maximum sectional area equals C_p.
2. The longitudinal center of area is the longitudinal center of buoyancy (LCB) of the ship, a number which can be estimated from speed and length.
3. The longitudinal position of maximum area, x_m, (not necessarily amidships).
4. The sectional area at the bow, y_1 (non-zero for a bulbous bow).
5. The section area at the stern, y_0 (non-zero for a transom stern).
6. The tangent to the curve at the bow, which can be estimated from resistance characteristics.

In the manual process the designer must draw a trial curve initially using a past similar design as a guide. Using numerical integration (Simpson's rule), he calculates both the area and center of area of the curve. This process must be repeated until C_p and LCB match the values fixed earlier in the cycle. In the author's computer-aided system, one analytical sectional area curve is generated immediately, using all of the above parameters including C_p and LCB as constraints. The method is described in detail in Section IV, "Computerization of Ship Design Calculations".

The next stage in the design is the generation of the hull form, generally done by a rough body plan sketch altered frequently until the desired sectional area curve is maintained, resulting in a preliminary lines plan. In a system of computer-aided design, at least two methods of hull generation presented themselves:

1. Polynomial representation of ship's lines as a function of input parameters -- in essence a rubberized ship.
2. A general technique of parametric three-dimensional surfaces which can be split and patched at will by a designer taking advantage of graphical man-machine communication.

The authors have chosen to employ the latter method in an effort to maintain maximum flexibility and to take fullest advantage of the speed and graphical input-output capabilities of the digital computer. It should be noted that work on the former method is also being carried on at M.I.T. in a branch of this same project. The method employed in this report is an analytic technique which is readily phrased in graphical terms and which was developed by Professor Steven A. Coons. The description of this method will be found in Section, III,"Theory and Properties of Parametric Surfaces".

The design of the hull is an iterative problem in either a computer-aided or manual system, the only differences being 1) the speed with which the designer can make and assess modifications and 2) the ease with which the designer (and other interested parties) can view the many aspects of his creation.

As described in the next section, the mathematics of Coons's surfaces has enabled the authors to program the computer to calculate quickly several surface properties which indicate to the naval architect whether this, indeed, is the desired hull form. At the present stage of this project, the quantities of displacement, C_p, KB, LCB, C_x, and wetted surface can be evaluated for any hull or portion of a hull; the framework also exists for future subroutines to calculate waterplane inertias, mass inertias, weight of shell plating, and eventually (given some loading patterns), stress distributions in hull plating.

Referring again to Fig. 2, we see that the designer modifies the inputs for hull description until he obtains a satisfactory size and shape. Once the hull form is established, the naval architect begins the arrangement of spaces (shown as sector number VII in the Design Spiral, Fig. 1) in order to find the answer to two critical questions:

1. Will this design have sufficient volume to contain all the required machinery and equipment?
2. Is the vertical center of gravity (KG) estimated by this arrangement low enough to assure sufficient stability for the ship?

A negative answer to either of these questions requires the naval architect to choose a new value for one or more of his input parameters and recycle. After a few recyclings, the designer should be able to satisfy all the major

requirements, including volume and stability, and he then can present his proposed ship.

Following the theoretical development of parametric surfaces in the next Section, the author's translation of this preliminary design process into a computer-aided design system is delineated in Section IV.

III. THEORY AND PROPERTIES OF PARAMETRIC SURFACES

A. INTRODUCTION

The ship example mentioned in the preliminary design discussion (see page 10) has shown the need for a convenient method of defining arbitrary surfaces. Surface description is necessary in almost any design problem and becomes an absolute necessity when the initiation of the building or manufacturing phase requires creation of the surface within specified tolerances. The designer or engineer is interested not only in the surface shape, but also in most of the various surface properties: area, volume, mass moment of inertia, cross-section inertia, center of gravity, resultants and equivalent points of application of external loads (both point and distributed loads), cross-sectional views, and views of the surface, including "hidden lines," as seen from various orientations.

A convenient descriptive technique is that originated by Professor Steven A. Coons in which a three-dimensional surface is modeled by two curvilinear parametric coordinates.* This section of the thesis will give a resume of the mathematics leading to the creation of Coons' surface and will use this surface formulation as the basis for the development of the various surface properties discussed above.

B. COONS' SURFACE

This portion of the thesis is by no means to be considered a complete derivation of Coons' surface. The mathematical background and the possibilities of Coons' surface are discussed in a paper by Prof. S.A. Coons of M.I.T.**

An automobile body designer, for example, is anxious to obtain a smooth fair surface that can be defined with a minimum of design curves. He would also appreciate having the capability of matching any desired order of derivative along the boundaries of two adjoining surfaces.

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* S. A. Coons, Surfaces for Computer-Aided Design of Space Figures, Unpublished Notes - Mechanical Engineering Department, M.I.T.

** Ibid.

Representing a space surface parametrically as follows,

$$x = x(u, w)$$

$$y = y(u, w)$$

$$z = z(u, w)$$

we assume a general form of the surface equation as

$$\begin{aligned}(uw) = {} & (0w)\,F_o(u) + (1w)\,F_1(u) \\ & + (u0)\,F_o(w) + (u1)\,F_1(w) \\ & - (00)\,F_o(u)\,F_o(w) - (01)\,F_o(u)\,F_1(w) \\ & - (10)\,F_1(u)\,F_o(w) - (11)\,F_1(u)\,F_1(w)\end{aligned}$$

where the x, y, or z is understood so that there are three of the above equations. Each term of these equations is composed of the product of a vector and the blending functions F_o and F_1. (u0), (u1), (0w), and (01) are vectors representing the boundary curves of the surface segment. (00), (01), (10), (11) are the corners of the surface segment.

By requiring the surface equation to contain the boundary curves, the following restrictions are placed on the blending functions:

$$F_o(0) = 1 \qquad F_1(0) = 0$$

$$F_o(1) = 0 \qquad F_1(1) = 1$$

If we impose additional restrictions on the blending functions

$$F_o'(0) = 0 \qquad F_1'(0) = 0$$

$$F_o'(1) = 0 \qquad F_1'(1) = 0$$

it will turn out that the boundary curve slopes are functions only of the corner slopes for the boundary.

If adjacent surface patches (or segments) are constrained to have this property, then surfaces of virtually any shape can be modeled by an assembly of such surface patches, and they will be continuous in slope across contiguous boundaries.

Letting the boundary curves of a surface patch be cubic polynomials and the blending functions be the cubics $F_1(u) = 3u^2 - 2u^3$ and $F_o(u) = 1 - F_1(u)$, the surface equations reduce to the bicubics:

$$(uw) = \sum_{i=o}^{3} \sum_{j=o}^{3} A_{ij} u^i w^i$$

This class of surface patch will have slope continuity along the boundaries and requires only the corner points and slopes to obtain the above formulation.

The surface property equations obtained in the following sections are true for any Coons' surface regardless of its specific equation form except for the cross-section and oriented-views sections in which the exact form of the surface equation is required to obtain the property under discussion. In both of the exceptional cases, however, the properties could be derived for any class of Coons' surface. Since these properties are dependent on the surface equation form, the only application of these sections is to the bicubic Coons' surface discussed above.

C. AREAS

The surface area of the differential element of Coons' surface may be obtained as the vector sum of the three projected areas, dA_x, dA_y, and dA_z; dA_x represents, typically, the projection of the area in the x direction onto the yz plane.

$$dA = dA_x + dA_y + dA_z$$

$$A = \int_S (dA_x + dA_y + dA_z)$$

The above formula is true <u>only</u> when the section of the surface to which it is applied is a close approximation to a plane; we will later investigate this restriction through the use of an example.

Assuming a differential element of surface area that may be approximated by a plane, we define an elementary vector dU which is

$$dU = idx + jdy + kdz$$

Differentiating our paramatric surface equations ($x = x(u, w)$, etc.), we have

$$dx = \frac{\partial x}{\partial u} du + \frac{\partial x}{\partial w} dw$$

$$dy = \frac{\partial y}{\partial u} du + \frac{\partial y}{\partial w} dw$$

$$dz = \frac{\partial z}{\partial u} du + \frac{\partial z}{\partial w} dw$$

Along a w-constant curve, the second terms on the right of these expressions vanish, and we can write

$$dU = i \frac{\partial x}{\partial u} du + j \frac{\partial y}{\partial u} du + k \frac{\partial z}{\partial u} du$$

Similarly, an elementary vector dW along a u-constant curve is given by

$$dW = i \frac{\partial x}{\partial w} dw + j \frac{\partial y}{\partial w} dw + k \frac{\partial z}{\partial w} dw$$

The vector product of these two elementary vectors is a vector whose magnitude equals the magnitude of the elementary area, and whose direction is normal to the dUdW plane. We have, for the vector dA

$$\begin{aligned} dA &= dU \times dW \\ &= (i \frac{\partial x}{du} + j\frac{\partial y}{\partial u} + k\frac{\partial z}{\partial u}) \times (i \frac{\partial x}{\partial w} + j \frac{\partial y}{\partial w} + k \frac{\partial z}{\partial w}) \, dudw \\ &= i(\frac{\partial y}{\partial u} \frac{\partial z}{\partial w} - \frac{\partial y}{\partial w} \frac{\partial z}{\partial u}) \, dudw \\ &+ j(\frac{\partial z}{\partial u} \frac{\partial x}{\partial w} - \frac{\partial z}{\partial w} \frac{\partial x}{\partial u}) \, dudw \\ &+ k(\frac{\partial x}{\partial u} \frac{\partial y}{\partial w} - \frac{\partial x}{\partial w} \frac{\partial y}{\partial u}) \, dudw \end{aligned}$$

which may be written in terms of jacobians as:

$$dA = (i \, J_x + j \, J_y + k \, J_z) \, dudw$$

where

$$J_x = \frac{\partial(y, z)}{\partial(u, w)} = \begin{vmatrix} \frac{\partial y}{\partial u} & \frac{\partial z}{\partial u} \\ \frac{\partial y}{\partial w} & \frac{\partial z}{\partial w} \end{vmatrix} \; ; \quad J_y = \frac{\partial(z, x)}{\partial(u, w)} = \begin{vmatrix} \frac{\partial z}{\partial u} & \frac{\partial x}{\partial u} \\ \frac{\partial z}{\partial w} & \frac{\partial x}{\partial w} \end{vmatrix}$$

$$J_z = \frac{\partial(x, y)}{\partial(u, w)} = \begin{vmatrix} \frac{\partial x}{\partial u} & \frac{\partial y}{\partial u} \\ \frac{\partial x}{\partial w} & \frac{\partial y}{\partial w} \end{vmatrix}$$

Since we wish to add up the magnitudes of the elementary area vectors, dA's, so as to obtain the total surface area magnitude, we define

$$dA_x = i \, J_x \, dudw$$

$$dA_y = j \, J_y \, dudw$$

$$dA_z = k \, J_z \, dudw$$

Now, the magnitude of the area vector dA is

$$|dA| = (dA \cdot dA)^{1/2}$$

and

$$dA \cdot dA = (dA_x + dA_y + dA_z) \cdot (dA_x + dA_y + dA_z)$$

so that

$$|dA| = (J_x{}^2 + J_y{}^2 + J_z{}^2)^{1/2} \, dudw$$

$$|A| = \int |dA| = \int_w \int_u (J_x{}^2 + J_y{}^2 + J_z{}^2)^{1/2} \, dudw$$

We may approximate the above expression by the numerical form

$$|A| = \sum |dA|$$

$$= \sum_w \sum_u (J_x{}^2 + J_y{}^2 + J_z{}^2)^{1/2} \, \Delta u \, \Delta w$$

So long as Δu and Δw are chosen sufficiently small, the above arithmetical operation will yield a satisfactory approximation to the total area magnitude.

The coordinates of our various patches may not form systems of a consistent hand (right- or left-handed). In the volume formulation, it is necessary to have all area vectors pointing in the same direction relative to the surface. Since the list structure of the surface as modeled by a computer will indicate which patches are tangent, we look at two cases: tangency and slope discontinuities.

D. TANGENCY

We obtain dA_I and dA_{II}, the elemental area vectors at a point P on the boundary of adjacent patches I and II. Since the patches are tangent, the area vectors are parallel. If the direction of dA_{II} is the same as dA_I, we have both vectors pointing either into or out of the volume enclosed by the surface. If the vectors are not pointing in the same direction, dA_{II} will be running in the $-dA_I$ direction since the patches are tangent. Thus, our area equation becomes,

$$A_i = (-1)^N \int_w \int_u (J_x i + J_y j + J_z k) \, dudw,$$

$$N = 0 \text{ initially}$$

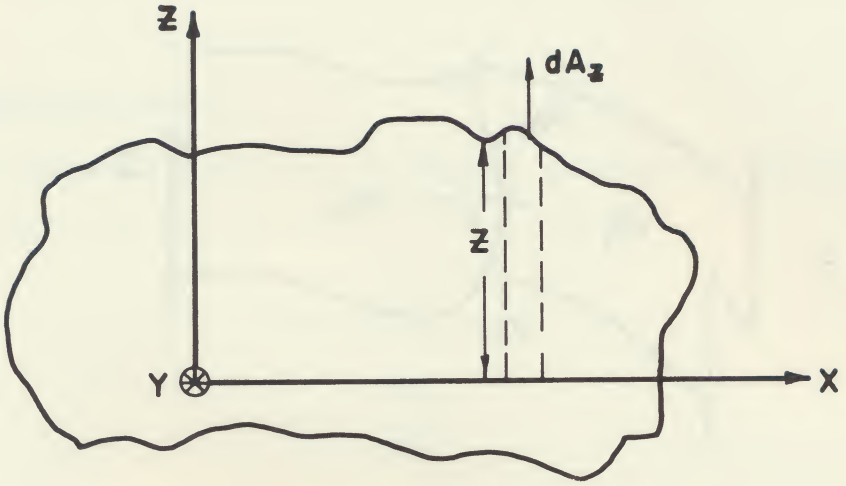

Fig. 4 Elemental Volume Calculation

As they stand, the above expressions will always provide a consistent sign for the volume, thus allowing the designed surface to occupy any or all of the octants created by the x, y, z coordinate system. Since the area vector, dA, of any element is directed perpendicular to the u, w coordinates of the surface, all area vectors on the surface will point either into or out of the surface since the tangency discussion has provided a consistent orientation method. Because of this ambiguity, the total volume, V, enclosed by a closed surface may be either positive or negative. Since volume is intrinsically a positive quantity, after the entire volume enclosed by the surface has been found, it must be positive, so

$$V = \left| \sum dV \right| = \left| \int_w \int_u kz \cdot dA_z \right|$$

$$V = \left| \int_w \int_u J_z \, z \, du dw \right|$$

G. MASS MOMENT OF INERTIA

Using our volume formulation, we can obtain the mass of a closed surface by taking a differential element of volume, dV, multiplying by the density, ρ, and integrating over the entire volume; thus

$$m = \int_V \rho \, dV$$

Since ρ may be a function of x, y and z, we cannot perform the above integration because our volume integral limits were on u and w, not on x, y, z. The coordinates u and w only exist on the surface of our volume so that x, y, and z in terms of u and w are only defined on the surface. While it would be possible to create a volume representation in terms of three parameters, u, w, and v, this thesis confines itself to a two-parameter surface. To approximate surfaces having a variable density, one can divide the interior into smaller closed surfaces each having a constant density; thus, the mass integral for each closed surface of constant density becomes

$$m = \rho \int_V dV$$

$$= \rho \int_w \int_u J_x \, x \, dudw$$

To obtain the coordinates of the center of gravity, we integrate the product of an elemental mass and the perpendicular distance to some arbitrary coordinate origin, and set the result equal to the mass times the center of gravity distance to the origin (t_c). Since the following formulations will hold for x, y, or z, we will let t and s stand for x, y, or z, so that

$$t_c = \frac{\rho}{m} \int_w \int_u t \, J_t \, t \, du \, dw$$

Defining the inertia of the constant density volume about the x, y, z coordinate system origin as I_T, the inertia of a point of mass equal to the mass of the volume placed at the center of gravity about the origin as I_A, and the inertia of the volume about its center of gravity as I_B, we have, by the parallel axis rule

$$I_T = I_A + I_B$$

The total inertia of the volume about each axis is

$$I_{T,\,ts} = \rho \int_V t\, s\, dV$$

$$= \rho \int_w \int_u t\, s\, J_t\, t\, du\, dw$$

Now

$$I_{A,\,ts} = 1/2\; m\, t_c\, s_c$$

Thus, using our parallel axis rule, we obtain as the inertia of the body about its center of gravity

$$I_{B,\,ts} = I_{T,\,ts} - I_{A,\,ts}$$

$$= \rho \int_w \int_u t\, s\, J_t\, t\, du\, dw - 1/2\, m\, t_c\, s_c$$

As an example, we want $I_{B,\,xz}$ so that $t = x$ and $s = z$, then

$$I_{B,\,xz} = \rho \int_w \int_u x\, z\, J_x\, x\, du\, dw - 1/2 m\, x_c\, z_c$$

Having obtained the inertias of our body in one coordinate system, we may proceed to obtain them in any other coordinate system by a tensor transformation.*

H. LOAD RESULTANTS

In many design applications, Coons' surface will be loaded with distributed and point loads. The engineer will want to know the resultants of these loads as well as the points of application of the resultants. In the ship design example, the stability of the ship depends on the location of the LCB and KB which are the points of application of the resultant load on the hull created by the buoyant force of the water.

Assuming all distributed loads, R, are applied normal to the surface and only on the surface, their resultants in the t direction where t is x, y, or z, are the following:

---

* R. Hill, Plasticity, page 342.

$$F_t = \int_s R(x, y, z)\, dA_t$$

$$= \int_w \int_u R(x, y, z)\, J_t dudw$$

A point load could be properly modeled by a distributed load so that the above would still apply.

To replace the distributed load with a resultant, the point of application of the resultant load must be such that its moment is the same as that of the distributed load. The moment created by the distributed load is

$$M_t = \int_s R(x, y, z)\, t dA_t = \int_v R(x, y, z)\, dV$$

and that of the resultant is $F_t \overline{t}$, where $\overline{t}$ is the point of application. Equating the above, we obtain

$$\overline{t} = \frac{\int_v R(x, y, z)\, dV}{\int_s R(x, y, z)\, dA_t}$$

Because all the loads are applied only on the surface, we may use our parametric representation where $x = x(u, w)$ to obtain

$$\overline{t} = \frac{\int_w \int_u R(u, w)\, J_t t\, dudw}{\int_w \int_u R(u, w)\, J_t dudw}$$

In the ship example, where the load is the water pressure on the hull, we have the situation shown in Fig. 5 so that, for example

$$LCB = \frac{\int_w \int_u zyJ_y dudw}{\int_w \int_u yJ_y dudw}$$

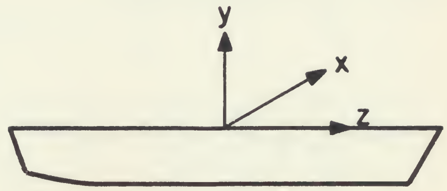

Fig. 5 Resultant Loads on a Ship

I. CROSS-SECTIONS

A cross-section of a surface is obtained by the intersection of the surface with an arbitrary plane of general equation $ax + by + cz + d = 0$. By proper coordinate rotation and translation, the plane equation can be reduced to $x = \text{constant}$. We must therefore find the intersection in u, w space of the plane and the surface.

The x-coordinate of the surface is represented by $x(u, w) = \sum_{i=0}^{3} \sum_{j=0}^{3} A_{ij} u^i w^j$

To reduce this equation to only one variable, we fix u or w so that intersections occur when the equation

$$A\alpha^3 + B\alpha^2 + C\alpha - \text{constant} = 0$$
$$(u = \text{constant},\ w = \alpha \ \text{ or } u = \alpha,\ w = \text{constant})$$

is satisfied. By fixing u, solving for w, incrementing u, and solving for w, we iterate across each patch obtaining a series of u's and w's satisfying the plane $x = \text{constant}$.

The particular patch being searched may not intersect with the plane, so we first search the four boundary curves whose x equations are a function of u or w only. If no intersections are obtained along the boundary curves, we continue to the next patch; if intersections do exist along the boundaries (intersections will always occur in pairs along the boundaries except for the three degenerate cases where the intersection is tangent to the boundary curve, the intersection occurs at the end of the curve, or a portion of the boundary curve lies in the plane), a search of the interior of the patch is initiated.

By picking the proper search direction, a quicker and better intersection curve can be obtained. If, for case AB in Fig. 6, the search were initiated

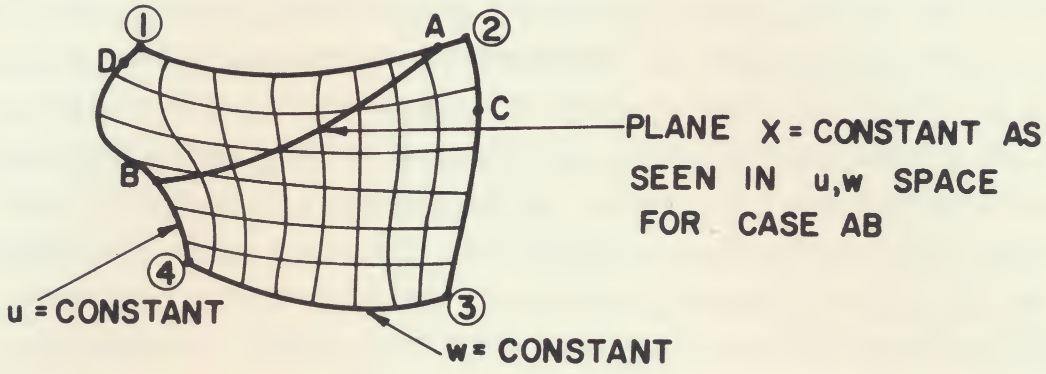

Fig. 6 Determination of Intersection Curve

along w = constant lines, the number of intersection points for a given w increment between searches would be much fewer than that obtained for a u = constant search with the same increment.

To obtain the best search direction for each of the possible intersection cases, we examine the following double plane-boundary curve intersections:

1) as in AB, the intersections are on u- and w-constant boundary curves. The slope of AB in x, y, z space is compared with the average of the u line slopes and the w line slopes at A and B in x, y, z space; the parameter whose slope average is closest to being perpendicular to the AB slope is chosen as the constant line. Thus, in AB, u would be fixed while the w satisfying the x = constant plane is evaluated, then u would be incremented and the search would continue.

2) as in BC, the intersections occur on two different lines having the same parameter constant. Here the parameter having the boundary curve - plane intersections is held constant while the search varies the other parameter. Thus, in BC, the w satisfying the plane would be found for a u = constant curve.

3) as in BD, the intersections occur along the same boundary curve so that the search is initiated along constant lines of the parameter having no plane-boundary curve intersections. Thus, in BD, the search fixes w while a u satisfying the plane equation is determined.

For the higher order (4, 6, 8, etc.) plane-boundary curve intersection cases, the same basic idea -- that of choosing as the constant parameter the one nearest to being perpendicular to the intersection -- still applies. The three previously mentioned degenerate cases require no interior searching and therefore no detailed discussion.

The various patches will all have u and w varying from zero to one. Since this does not mean they are to the same scale in x, y, z space, using the same sized u or w increment in the search process could cause a large variation in the spacing of the intersection points when plotted in their final form -- a curve in yz space. To obtain more even spacing of intersection points in yz space, the relative scales of each boundary curve must be considered. As a first approximation, the length of the boundary curves could be compared with some base length, and an arbitrary scale factor could be inserted, thus varying the increment size. For each patch, the length of the two u = constant boundary curves and that of the two w = constant boundary curves would be compared to some base length. It should be pointed out that this is only a crude attempt since the patch can be shaped such that the approximation is scarcely beneficial; for example, in the patch shown in Fig. 7, the approximation would give good results when

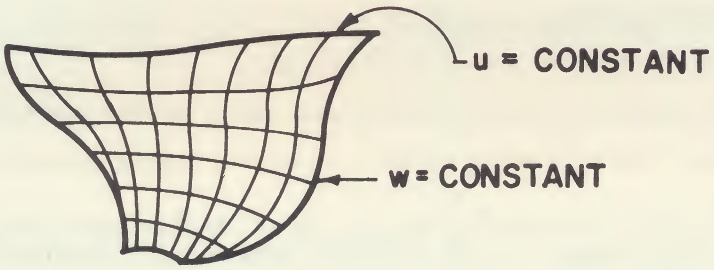

Fig. 7 Example of Increment Spacing Problems for Odd-Shaped Patch

applied to the u = constant curves but along the w = constant curves, would ignore the variation in the increment spacings with a variation in u.

The above cross-section discussion has not been tested by the authors. The possible methods examined should be tested so that a more concise and quicker cross-section could be obtained. At this writing, the authors have attempted to design their surfaces so that either a u- or w-constant line closely approximates a cross-section; this expedient is recommended until further work is done in this field.

J. PLANAR INERTIAS

The plot of points of the plane-surface intersection may now be used to determine the inertia of that cross-section of the surface. We first connect the series of points together using either straight lines or, for a more exact fitting technique, we may use a polynomial fit. Since the accuracy increase of the polynomial fit over a straight line fit will be small for close-spaced points, and since the amount of labor to create a polynomial fit is greater than that for a straight line, we would look at a straight line fit only.

The centers of area and inertias of polygons may be obtained easily as sums.* These results would be used in the ship design process to obtain the waterplane intertia, I_{wp}, used in calculating the metacentric height:

$$KM = KB + BM = KB + \frac{I_{wp}}{\nabla}$$

where KM = Metacentric height

KB = Vertical center of buoyancy

BM = Distance between center of buoyancy and metacenter

∇ = Displacement volume

K. ORIENTED VIEWS

An engineering drawing will include various orientations of an object showing not only those portions that the eye would see but also all places where the surface of the object runs parallel to the direction the eye is looking. Some of the parallel portions are hidden from sight and as such are shown as dotted or "hidden" lines. For an arbitrary viewing direction, the body may be rotated such that the x-direction becomes the viewing position. At all portions of the surface parallel to the x-direction, the slope of the surface in the x-direction is zero, that is,

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* W. C. Hamann, Computer-Aided Design of Slender Structural Members, Appendix A.

$$\frac{dx}{ds} = 0.$$

Now,

$$dx = \frac{\partial x}{\partial u}\, du + \frac{\partial x}{\partial w}\, dw$$

so that

$$\frac{dx}{ds} = \frac{\partial x}{\partial u}\frac{du}{ds} + \frac{\partial x}{\partial w}\frac{dw}{ds}.$$

If we fix, for example w, we have $\frac{dw}{ds} = 0$ so that

$$\frac{dx}{ds} = \frac{\partial x}{\partial u}\frac{du}{ds}$$

Since $\frac{dw}{ds} = 0$, $\frac{du}{ds} \neq 0$ so for parallelity we have

$$\frac{\partial x}{\partial u} = 0 \text{ for } w = \text{constant}$$

and

$$\frac{\partial x}{\partial w} = 0 \text{ for } u = \text{constant}$$

In Coons' surface representation x is a bicubic in terms of u and w. Letting α be u or w, the restriction $\frac{\partial x}{\partial \alpha} = 0$ is a quadratic

$$A\alpha^2 + B\alpha + C = 0$$

As in the Cross-Sections discussion, page 24, we now look for solutions to the above equation. Here, however, we may analytically solve the quadratic accepting only real roots lying between 0 and 1, the limits on u and w. The quadratic is solved for the four boundaries of each patch and only if roots between 0 and 1 are obtained is it necessary to solve in the interior. Since we are using analytical solutions rather than the residue techniques employed in the Cross-Sections discussion, our choice of which coordinate to fix makes no difference.

Two problems now present themselves; a method of determining which of our parallel points create a closed contour of the surface, and how to determine which of these contours or portions of them would be seen by a viewer and which parts are hidden and as such should appear as dotted lines. The authors have not found solutions to these problems and recommend that future work be concentrated on a completion of both the cross-section and oriented views sections of this thesis.

IV. COMPUTERIZATION OF SHIP DESIGN CALCULATIONS

A. INTRODUCTION

The computer-aided ship design calculations can be divided into two categories:

1. Preliminary estimates of hull dimensions, form coefficients, weights, and powers.
2. Evaluation of hull properties resulting from the design of one particular hull surface.

In this section the author's programs and underlying assumptions for each of these categories of calculations are explained.

B. WEIGHT-POWER PROGRAM

Since the authors were concerned with a complete computer-aided system for feasibility design studies, a short, straightforward program to estimate weights and powers was written. However, because these calculations were of a routine nature, most of the time in this project was spent in the development of programs for the more elusive problems of hull description and evaluation.

Briefly, the weight-power program, WTPOWR, begins with a set of data input by the designer at his time-sharing console and proceeds to print out for the designer a solution to the weight equation, and,if desired, a speed-power curve (EHP and SHP over a complete range of speeds) and a weight breakdown for each of the major weight categories. When this program is in execution, there is a continuous dialogue between designer and computer such that the man can change any of his input items and ask the machine to assess the effects of that change on any of the above outputs. A flow diagram, Fig. 8, describes schematically the operation of WTPOWR.

The calculations described above were made using modified Taylor Standard Series data for residual resistance. The data was expanded to cover the entire matrix of:

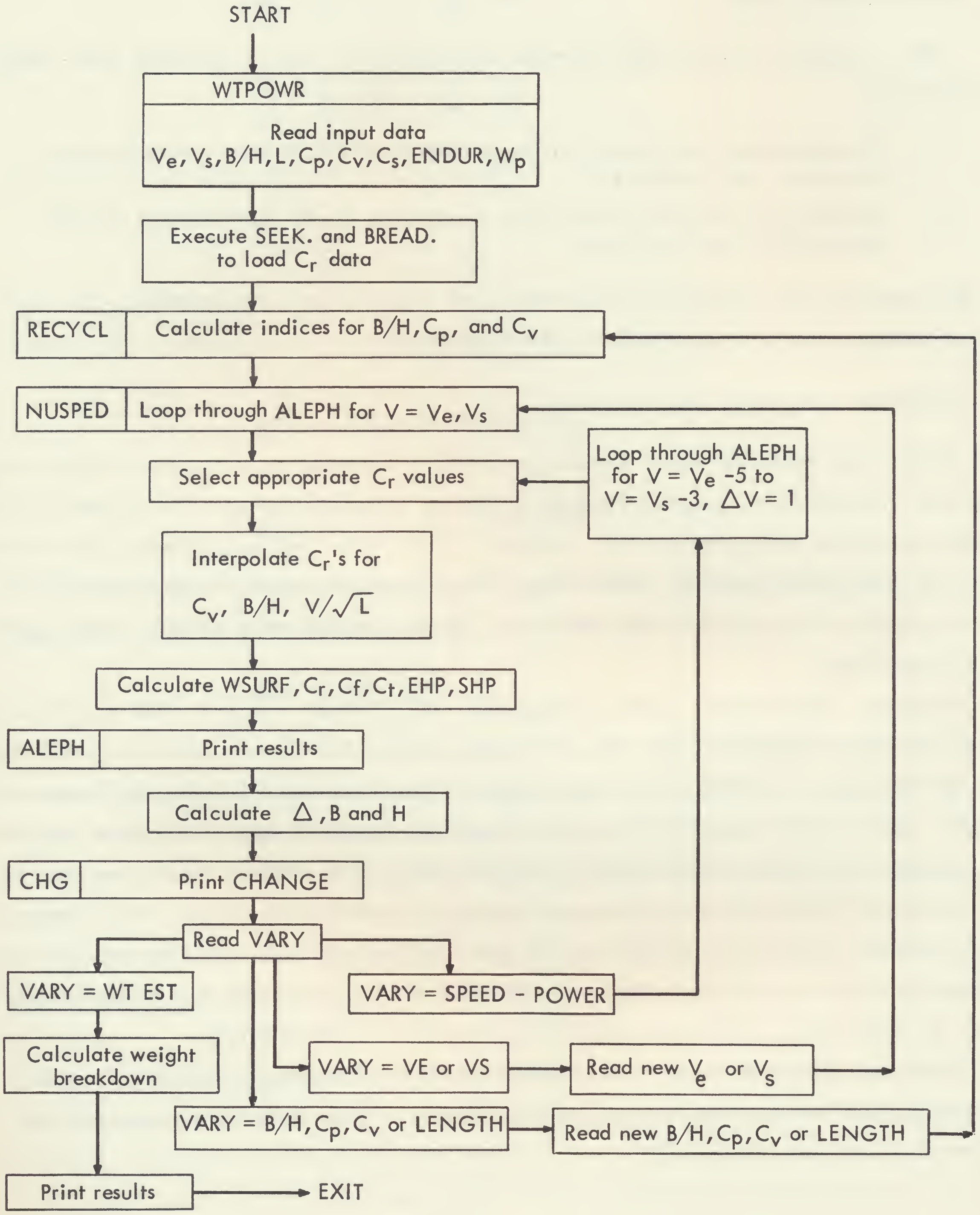

Fig. 8 Flow Diagram for Program WTPOWR

$C_p = 0.55$ to 0.65

$C_v = 1.0 \times 10^{-3}$ to 3.0×10^{-3}

$B/H = 2.25$ to 3.75

$V/\sqrt{L} = 0.75$ to 2.00

in the following manner:

1. Taylor C_r data,* modified by appropriate coefficients for destroyer hull forms,** were used for $V/\sqrt{L} = 0.75$ to 1.00.
2. A Davidson Laboratory high-speed report† was used for data in the range of $V/\sqrt{L}$ from 1.30 to 2.00.
3. Data for $V/\sqrt{L} = 1.00$ to 1.30 were obtained by fairing the Taylor data at $V/\sqrt{L} = 1.00$ into the Davidson data at $V/\sqrt{L} = 1.30$.
4. IBM cards were punched with all values of C_r in the above matrix, CR(1)...CR(2574).
5. A small program, READIN, was written to convert the decimal data on cards into a binary file in the author's time-sharing file directory.

Frictional resistance was calculated by

$$C_f = \frac{.075}{(\log_{10} R_e - 2)^2}$$

where R_e = Reynolds No., a curve fitting formulation which coincides with the ATTC (Schoenherr) friction line at ship speeds. Calculations were based on an assumed temperature of 59° F.

Finally, a roughness allowance of .0005 was assumed, and wetted surface was calculated by:

$$\text{WSURF} = \frac{C_s L^2 \sqrt{C_v}}{31.62}$$

where

C_s = Saunders' wetted surface coefficient.‡

L = Length on waterline.

C_v = Volumetric coefficient.

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* M. Gertler, A Reanalysis of the Original Test Data for the Taylor Standard Series, DTMB Report No. 806.

** Mandel, op. cit., Figure 1.

† Van Mater, Zubaly and Beys, Hydrodynamics of High Speed Ships, Davidson Laboratory R-876.

‡ Saunders, op. cit.

All weight categories and weight relationships used in WTPOWR were taken from Professor Mandel's paper on destroyer-cruiser weights.*

C. SECTIONAL AREA CURVE PROGRAM

The second instance of computer application to preliminary form estimates was the development of a program, SACURV, to present the naval architect with one sectional area curve -- one which would meet all the requirements (C_p, LCB, etc.) fixed at that stage of the design just prior to the hull form definition.

It should be emphasized that this program gives the designer a simple graphical aid as a starting point. The sectional area curve so produced will not necessarily be the final curve of the hull eventually proposed in the feasibility study. It will,however, be an excellent guide and reference point for the designer as he begins to lay out his hull form on SKETCHPAD. While the hull generator program is presently set up to calculate and point out only C_x, it is envisioned that in the near future it will be possible for the designer to request the area of any section drawn and so have a feedback to compare with his sectional area curve guide.

In an attempt to model analytically a sectional area curve for a destroyer-type hull, several approaches were tried. Among these were ordinary third-, fourth-, and fifth-order polynomials, but the method of parametric cubics was finally chosen because of its flexibility, its inherent "reasonable" behavior, and its compatibility with the mathematics of the surface generation techniques.

The method developed here is one in which the entire sectional area curve is made up of two parametric (or rotated space) cubics, as shown below in Fig. 9. Following is a brief summary of the method; a complete derivation is given in Appendix B.

* Mandel, op. cit.

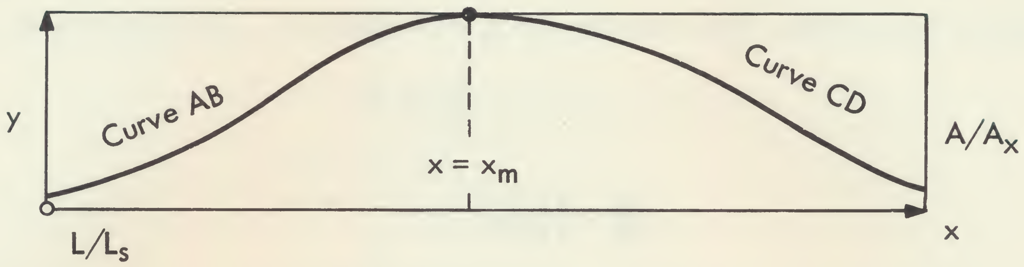


Fig. 9 Sectional Area Curve

Each curve, AB and CD, has its x and y coordinates represented as cubic functions of the parameter, u:

For curve AB

$$x = A_1u^3 + A_2u^2 + A_3u + A_4$$
$$y = B_1u^3 + B_2u^2 + B_3u + B_4$$

For curve CD

$$x = C_1u^3 + C_2u^2 + C_3u + C_4$$
$$y = D_1u^3 + D_2u^2 + D_3u + D_4$$

As shown in Fig. 9, the x and y coordinates have been non-dimensionalized as L/L_s and A/A_x, respectively, making their limits 0 and 1. The parameter u varies from 0 to 1 on each curve, i.e., for $x = 0$ to $x = x_m$ on curve AB and for $x = x_m$ to $x = 1$ on curve CD.

We wish to apply the following restrictions to these curves:

1. Stern area -- $x = 0$, $y = y_0$, $u = 0$
2. Bow area -- $x = 1$, $y = y_1$, $u = 1$
3. Position of maximum area, curve AB -- $x = x_m$, $y = 1$, $u = 1$
4. Position of maximum area, curve CD -- $x = x_m$, $y = 1$, $u = 0$
5. Slope at maximum area -- $x = x_m$, $dy/dx = 0$
6. Tangent to curve at bow -- $x = 1$, $\frac{dy}{dx} = t$, $u = 1$
7. Area under curve -- $\int AB(x)dx + \int CD(x)dx = C_p$
8. Center of area -- $\int xAB(x)dx + \int xCD(x)dx = C_p \cdot LCB$

The inputs x_m, y_0, y_1, C_p, LCB, and t are readily determinable at this stage, but these alone are not sufficient to fix all the coefficients, A, B, C, and D, in the above equations. This can be seen, for example, in condition no. 5:

$$x = 1, \quad u = 1, \quad \frac{dy}{dx} = t$$

but

$$\frac{dy}{dx} = \frac{\partial y/\partial u}{\partial x/\partial u} = t$$

Thus, the ratio of the parametric slopes equals the tangent at the bow in xy space, but, since either $\partial x/\partial u$ or $\partial y/\partial u$ is arbitrary, an additional degree of freedom now exists in parametric space. Experience here has indicated that the choice of $\frac{\partial x}{\partial u}$ in the range of .01 to .05 results in a curve of the desired shape. Similar arbitrary choices were made as follows:

1. $x = x_m$, $\frac{dy}{dx} = 0$, $u = 1$ --- $\frac{\partial x}{\partial u}$ in the range of 0.2 to 1.0
2. $x = x_m$, $\frac{dy}{dx} = 0$, $u = 0$ --- $\frac{\partial x}{\partial u}$ in the range of 0.2 to 1.0

These three parametric slopes become, in effect, spline stiffness factors so that a wide range of a family of curves can be obtained. It was found, however, that because of the interdependent nature of the constraints and spline factors, there is only one value of $\partial x/\partial u$ at $x = x_m$, $u = 1$, which will satisfy both the area and center of area equations, given all other variables. As a result, the designer using this program must specify his inputs (x_m, y_0, y_1, t, C_p, and LCB), choose two parametric slope parameters (xu0 and xu1), and then try a value for XU SLOPE AT XM FOR STERN. The computer will respond by typing out the resulting LCB for a sectional area curve determined by the method described. If the LCB of this curve is close enough to the desired LCB, the designer can request the computer to print out the curve coordinates or to make a rough plot on the teletype. If the calculated LCB is too low, the designer must specify a smaller XU SLOPE XM FOR STERN and the process will be repeated; if the LCB value is too high, the new slope specified should be higher. A little experience, perhaps a few hours, is needed to gain a feel for the numbers involved.

The derivation of the equations and coefficients used in SACURV can be found in Appendix B. Figure 10 is a flow diagram of the program as it was being developed.

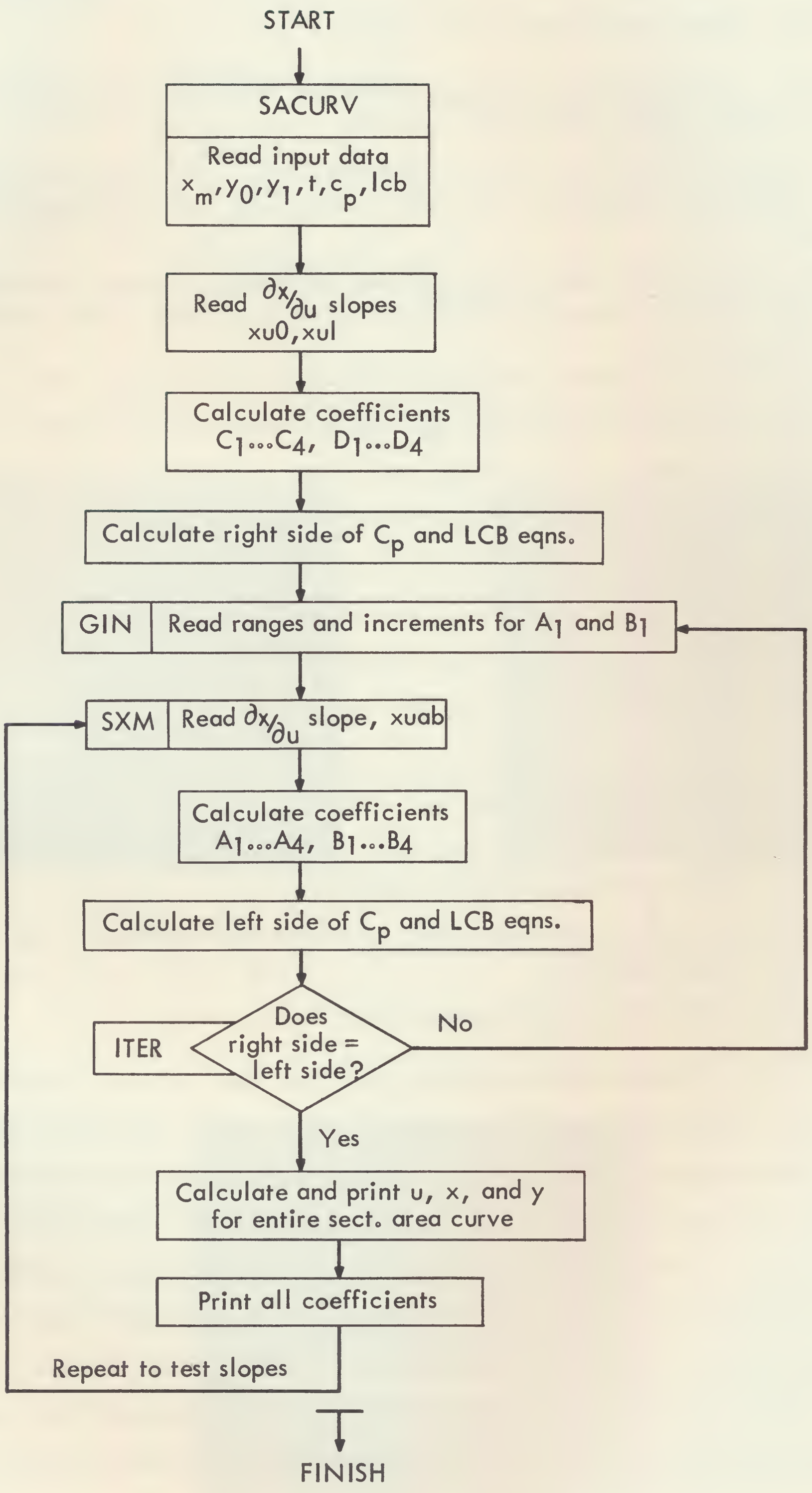


Fig. 10 Flow Diagram of Program SACURV

D. SURFACE GENERATION AND EVALUATION PROGRAMS

In the second category, namely the generation of the hull and evaluation of hull properties, three programs are used:

1. SURFAC - establishes a Coons' bicubic surface for scope display using point and slope inputs
2. GEN - calculates hull surface properties, i.e., wetted surface area, enclosed volume, C_x, KB, and LCB, as requested by the designer
3. TANGT - examines tangency of two adjacent surface patches to fix appropriate signs to surface area vectors of the patches

The program SURFAC was written by Richard Parmelee and Charles Garman of the CAD Group to generate the numerical data necessary for the display of any surface patch. The program implements Coons' mathematics for bicubic surfaces and is sufficiently general so that sections of spheres, car fenders, tobacco pipes, and ship hulls can be designed. Since it was found that the entire surface patch can conveniently be defined by four corner points on the patch and the slopes to the boundary curves at these points, the inputs necessary to design a portion of the hull are the following:

1. the x, y, z coordinates of the four corner points on the surface (some points may be coincident)
2. the vector slopes Δx, Δy, and Δz for both u- and w-constant curves at each corner point
3. scale factors and mesh size (the number of constant u and w lines to be displayed)
4. an indication of the blending function to be used

It was found that at least two surface patches (one forward and one aft of midships) were needed to describe a destroyer hull, and that both the magnitudes and directions of the vector slopes provided full control over the shape of the hull. As an example, the sketch in Fig. 11 describes the points and slopes needed for the bow half of the ship. The midship section is fixed in the xy-plane so that the w constant lines along the surface will appear very nearly as section planes in a body plan. The lengths of the slope vectors along the w = 1 curve at points 2 and 4 control the fullness of the midship section, as shown in three forebody pictures taken from the scope face (Fig. 12).

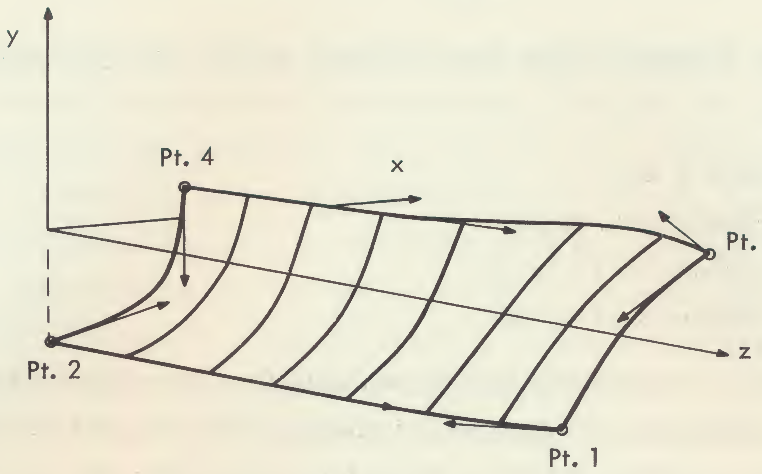
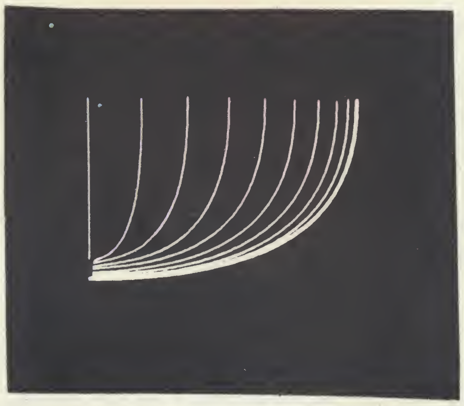
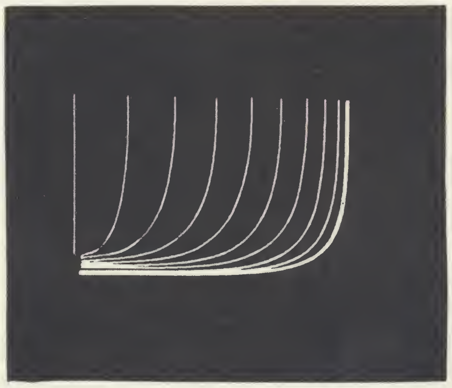


Fig. 11 Points and Slopes for Bow Half of Ship



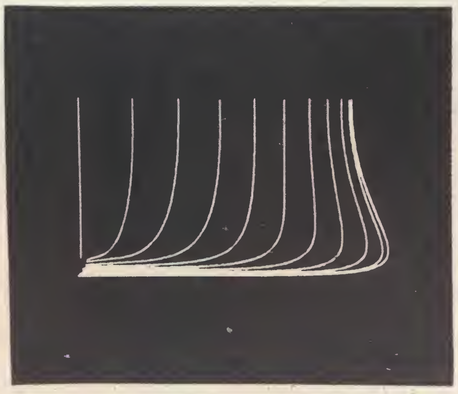
$C_x = .84$

u slopes, Δx, Δy, Δz
Pt. 2: 20, 0, 0
Pt. 4: .1, 13, 0



$C_x = .95$

u slopes, Δx, Δy, Δz
Pt. 2: 29, 0, 0
Pt. 4: .1, 19, 0



$C_x = 1.10$

u slopes, Δx, Δy, Δz
Pt. 2: 50, 0, 0
Pt. 4: .1, 19, 0

Fig. 12 Control of Midship Section

For a ship with a bulbous bow and transom stern, the hull might be made up of four patches:

1. bulb - Stations 0 to 2
2. forebody - Stations 2 to 10
3. afterbody - Stations 10 to 18
4. transom - Stations 18 to 20

By choosing the same magnitudes and directions for the slopes where the patches meet, the designer can guarantee slope continuity across his entire surface. At present, patches must be designed separately and pieced together photographically, but when the work of Tim Johnson and others on the SKETCHPAD data structure is completed, the data for each patch will be stored in the computer and will be pieced together for display and for calculations of hull properties as one complete surface. Thus, at present, it is necessary to design first the hull below the load waterline so that calculations of C_x, wetted surface, and C_p will be meaningful. After these properties agree with the designer's earlier choices from the WTPOWR program, the design can then progress to the hull above the waterline and eventually, to superstructure.

When the methods of hull delineation developed here are extended to the actual, complete preliminary design of ships in future years, it is probable that a ship, including superstructure, may be made up of twenty or thirty patches plus a few correction surfaces in order to mold the basic surface treatment to actual needs. That such a design method is feasible is demonstrated by the success of the one- and two-patch designs described here and in Chapter V. However, it is also clear that the eventual complexity of such a system will be many times greater than it is presently and thus, the need for more and continued graphical input as well as output mounts in importance. For this reason, work is now being carried on toward the replacement of the present numerical teletype inputs with graphical light pen inputs for the design of surface patches.

The last two programs, GEN and TANGT, use the surface information created by SURFAC to obtain the coefficients (a_{ij}) of the bicubic equations for x, y, and z. Using these coefficients, GEN calculates the surface area of the ship by an iteration process employing the area equations derived in Section III. For the below-waterline portion of the hull, this corresponds

to total wetted surface (when both bow and stern patches are combined.)

The volume is calculated by evaluating $\int zJ_z \, du \, dw$. For a closed surface, any of three integrals, xJ_x, yJ_y, or zJ_z, would yield the same result, but in the ship case, the surface is not closed, so care must be taken to assure that the ship is oriented such that the integral of J_z over the surface gives the desired volume. This orientation for the bow is shown in the sketch on page 24. The stern patch would extend from the xy-plane into the octant where x, y, and z are all negative.

GEN calculates C_x by assuming that the maximum area section lies in the $z = 0$ plane and corresponds to the $w = 1$ curve on the surface. The mid-ship area is calculated directly by integrating the coefficients for that curve, and C_x is found by dividing that area by the product of beam and draft.

A request of "STABILITY" by the designer will cause GEN to calculate KB and LCB by taking vertical and horizontal volume moments:

$$M_v = \text{vertical moment} = \int yx \, J_x \, du \, dw$$

$$M_h = \text{horizontal moment} = \int zx \, J_x \, du \, dw$$

and then dividing by the displacement volume:

$$CB = \frac{M_v}{\nabla} \quad , \qquad KB = H - CB$$

where H = draft, CB = center of buoyancy, feet below WL

$$LCB = \frac{M_h}{\nabla}$$

Finally, the program TANGT examines tangencies of adjacent patches of surface as described in Section III. This program was not used in the examples studied in this thesis since the mechanism for piecing surface patches together in the data structure was not available.

V. EXAMPLE OF DESTROYER DESIGN

In this section an example is given of a destroyer design. The inputs used are the characteristics of an existing destroyer, DD 692, so that it could be seen how close the resulting design is to the final ship.

The first page of the example shows that after two lines of input information, the computer prints out 1) resistance and powering data for endurance and sustained speeds, 2) estimated wetted surface, beam, draft, and 3) displacements ("guess," from L and C_v and "iterative," from empirical sum of weights). The request, "speed-power," typed in by the designer, produces a speed-power table for a full range of speeds, as does "wt estimate" for a table giving estimated weight breakdown.

The second page shows the sectional area curve for the example design, which is compared in Fig. 13 with the actual DD 692.

Finally, the last pages of this section show the teletype input necessary to describe the hull surface by two patches -- a bow patch, Stations 0 to 11 and a stern patch, Stations 11 to 20. Pictures showing the designed hull were photographed from the display scope and are presented in Figs. 14, 15, and 16. The several hull properties now available, wetted surface, volume, C_x, and centers of buoyancy, are shown following the numerical input data.

```
loadgo wtpowr
W 025.2
EXECUTION.
VE= VS= LE=  BH=  CP= CV=  CS=  CX=
20. 30. 369. 3.19 .6251.92 2.63 .83

ENDURANCE IN MILES=   PAYLOAD WT.=
4000.                  220.

VL=1.04
V=20.0 KNOTS
SHP=   8826.
CF=0.00204 CR=0.00124 CT=0.00328

VL=1.56
V=30.0 KNOTS
SHP=  42971.
CF=0.00196 CR=0.00318 CT=0.00514

WETTED SURFACE=  15693. SQ. FT.
BEAM=   40.1 FT.
DRAFT=   12.57 FT.
GUESS=  2756.  ITERATIVE DISPLACEMENT=    2805.
CHANGE
speed-power
```

V	VL	EHP	SHP
15.00	0.78	1293.	3259.
16.00	0.83	1596.	4021.
17.00	0.88	1979.	4909.
18.00	0.94	2461.	6102.
19.00	0.99	3004.	7390.
20.00	1.04	3587.	8826.
21.00	1.09	4172.	10182.
22.00	1.15	4793.	11698.
23.00	1.20	5623.	13610.
24.00	1.25	6773.	16395.
25.00	1.30	8304.	19606.
26.00	1.35	10171.	23410.
27.00	1.41	12268.	28237.
28.00	1.46	14465.	33006.
29.00	1.51	16752.	38223.
30.00	1.56	18998.	42971.
31.00	1.61	21287.	48149.
32.00	1.67	23609.	52932.
33.00	1.72	25952.	58187.

```
CHANGE
wt estimate
```

WEIGHT ITEM	WEIGHT IN TONS
***********	**************
HULL STRUCTURE	827.
MACHINERY	460.
MACHY. FOUNDATIONS	32.
MACHY. LIQUIDS	57.
ELECTRIC PLANT	108.
AUXILIARIES	425.
COMPLEMENT + STORES	94.
FUEL	584.
PAYLOAD + BALLAST	220.

```
  EXIT CALLED. PM MAY BE TAKEN.
R 6.200+8.016
```

```
loadgo sacurv
W 1243.1
EXECUTION.
XM=    Y0=    Y1=    T=     CP=    LCB=
.45    .095   .00    -6.    .625   .48
xu0=    XU1=
.58     .025
IA  JA  KA
.55 .01 .75
IB  JB  KB
-.2 .01 .00
XU SLOPE AT XM FOR STERN=
.67
TOLERANCES
.002.002

*************************

  U    X    Y
 0.   0.   0.09
 0.05 0.04 0.18
 0.10 0.08 0.26
 0.15 0.11 0.34
 0.20 0.14 0.42
 0.25 0.16 0.49
 0.30 0.18 0.55
 0.35 0.20 0.61
 0.40 0.22 0.67
 0.45 0.24 0.72
 0.50 0.25 0.77
 0.55 0.26 0.81
 0.60 0.28 0.85
 0.65 0.29 0.89
 0.70 0.31 0.92
 0.75 0.33 0.94
 0.80 0.35 0.96
 0.85 0.37 0.98
 0.90 0.39 0.99
 0.95 0.42 1.00
 1.00 0.45 1.00
  U    X    Y
 0.   0.45 1.00
 0.05 0.48 0.99
 0.10 0.51 0.97
 0.15 0.55 0.94
 0.20 0.58 0.90
 0.25 0.62 0.85
 0.30 0.65 0.79
 0.35 0.69 0.73
 0.40 0.72 0.66
 0.45 0.76 0.59
 0.50 0.79 0.52
 0.55 0.83 0.45
 0.60 0.86 0.37
 0.65 0.89 0.30
 0.70 0.91 0.24
 0.75 0.94 0.18
 0.80 0.96 0.12
 0.85 0.97 0.08
 0.90 0.99 0.04
 0.95 1.00 0.01
 1.00 1.00-0.
```

INPUTS	
C_p	.625
LCB	.48
X_m	.45
y_o	.095
y_1	.0
t	−6.0

PARAMETER	SLOPES
XuO	.58
Xu1	.025
Xum	.67

COEFFICIENTS	
A_1	.64
B_1	−.03

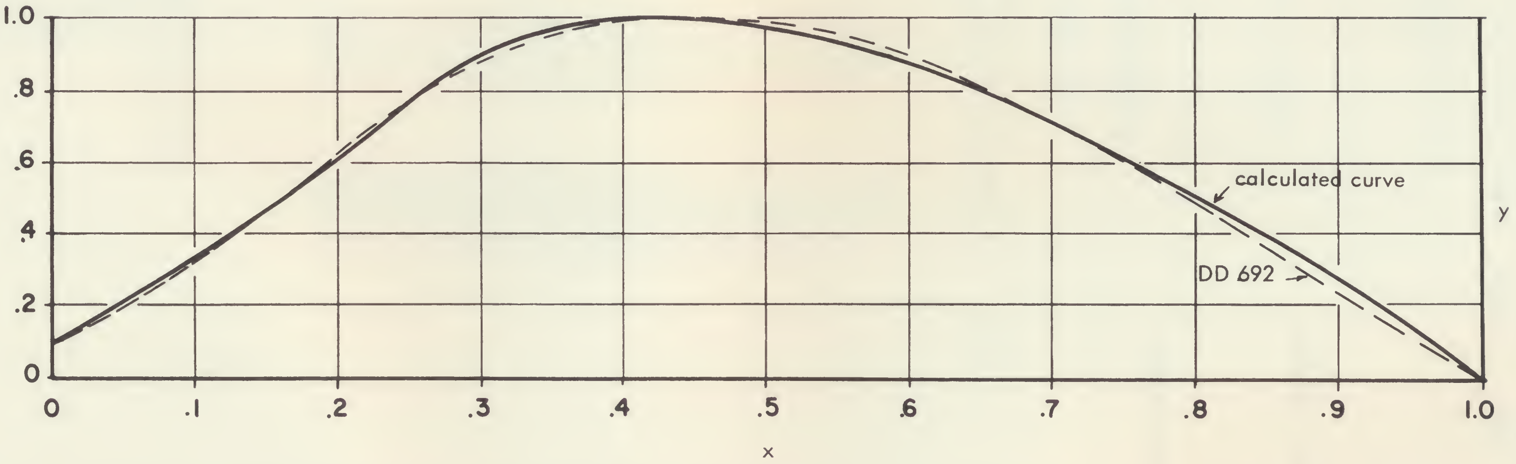


Fig. 13 Sectional Area Curve DD 692

```
resume r ctest3 vload surfac (get) ttylst / start
W 1954.8
DORMNT ALREADY LOADED
TYPE E.P. (X,Y,Z):
EP 1
0,-11.2,201
EP 2
0,-12.5,0
EP 3
0,0,203
EP 4
19.5,0,0
TYPE SLOPES:
EP 1
0,1.5,1
0,-.6,-.4
EP 2
18.4,0,0
0,0,-180
EP 3
0,1.5,1
6,0,-30
EP 4
.1,13,0
0,0,-155
TYPE M AND N:
10,20
TYPE B:
0
TYPE CENTERS:
10,-5,100
TYPE SCALE:
.06
CHANGE:

midships
CX= 0.830270E 00
CHANGE:

volume
VOLUME=-0.262240E 05
CHANGE:

stability
LCB= 0.739357E 02   KB= 0.787903E 01
CHANGE:

area
LCB= 0.739357E 02   KB= 0.787903E 01
CHANGE:
A= 0.399553E 04     MARG=     1
A= 0.408625E 04     MARG=     2
a1 0.410988E 04     MARG=     3
A= 0.410988E 04     MARG=     3
CHANGE:
```

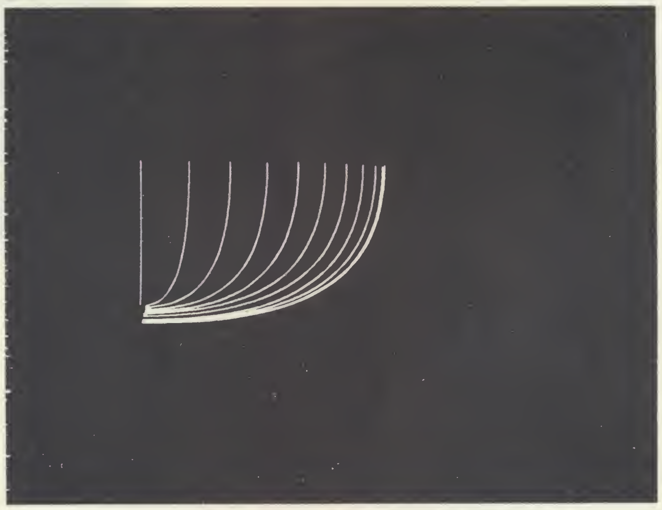


Fig. 14 Bow Below Waterline

```
surface
TYPE E.P. (X,Y,Z):
EP 1
-19.5,0,0
EP 2
-10.5,0,-165
EP 3
0,-12.5,0
EP 4
0,-2.5,-167
TYPE SLOPES:
EP 1
.1,-13,0
0,0,-10
EP 2
2,-1,-2
10,0,-40
EP 3
18.4,0,0
0,0,-150
EP 4
18,-3,-1
0,12,-96
TYPE M AND N:
10,20
type b4
0
TYPE CENTERS:
-10,-5,-85
TYPE SCALE:
.06
CHANGE:

volume
VOLUME=-0.219881E 05
CHANGE:

stability
LCB=-0.625612E 02    KB= 0.301908E 01
CHANGE:

area
A= 0.343352E 04      MARG=      1
A= 0.348554E 04      MARG=      2
A= 0.348554E 04      MARG=      2
CHANGE:
```

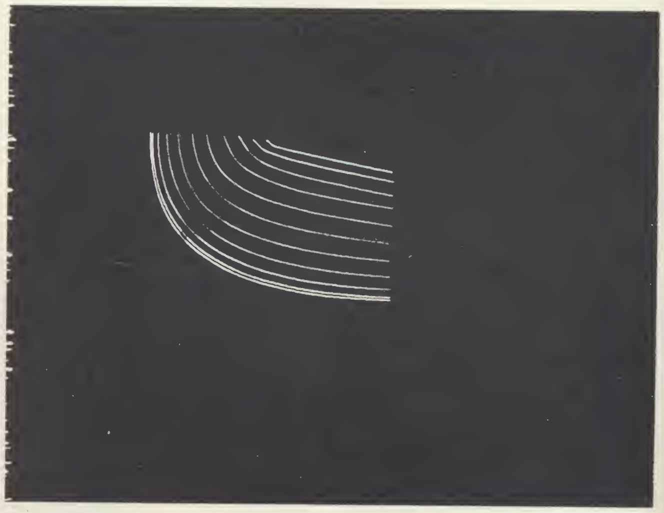


Fig. 15 Stern Below Waterline

(Note: This is CB, the distance below waterline to actual center of buoyancy. Thus, KB = H - CB = 12.5 - 3.0 = 9.5.)

Total volume = 96,420 ft.^{3}

Total displacement = 2755 tons

Net LCB = .481 (1.9% aft of midships)

Net KB = 8.64 ft.

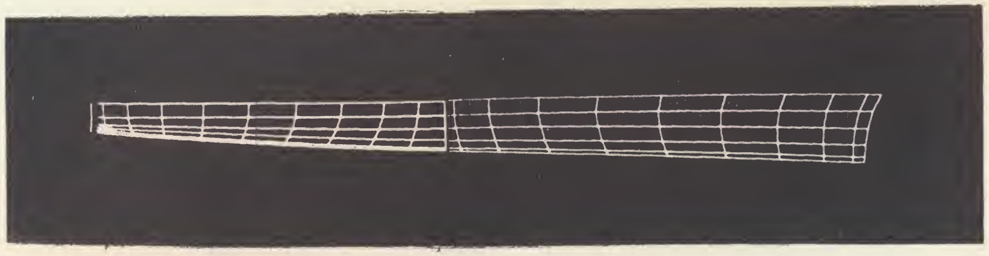
Total wetted surface = 15,192 ft.^{2}

Full Bow

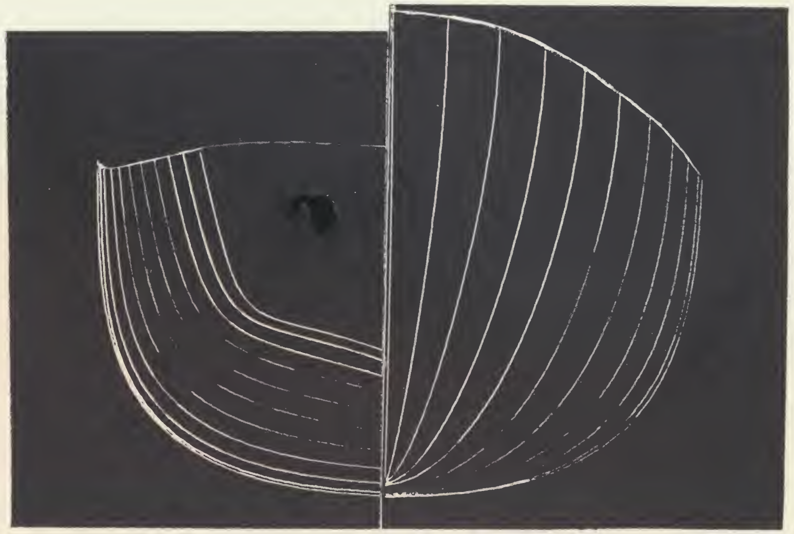
```
surface
TYPE E.P. (X,Y,Z):
EP 1
0,-11.2,201
EP 2
0,-12.5,0
EP 3
0,19.75,208
EP 4
22,9.5,0
TYPE SLOPES:
EP 1
0,1,1
0,-.5,-.1
EP 2
31,0,0
0,0,-30
EP 3
0,18,12
20,0,-5
EP 4
.1,16,0
0,-1,-9
TYPE M AND N:
10,20
TYPE B:
0
TYPE CENTERS:
11,3.5,104
TYPE SCALE:
.06
CHANGE:

volume
VOLUME=-0.625930E 05
CHANGE:

area
A= 0.674344E 04      MARG=        1
A= 0.689166E 04      MARG=        2
A= 0.693439E 04      MARG=        3
A= 0.693439E 04      MARG=        3
CHANGE:
```

Full Stern

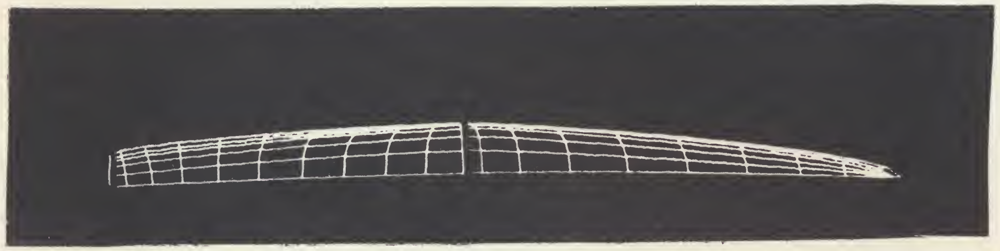
```
surface
TYPE E.P. (X,Y,Z):
EP 1
-20,9.5,0
EP 2
0,-12.5,0
EP 3
-13,10.5,-166
EP 4
0,-2.5,-167
TYPE SLOPES:
EP 1
.1,-16,0
0,-2,-45
EP 2
5,-20,0
6,1,-9
EP 3
31,0,0
0,0,-80
EP 4
16,-5,0
0,3,-30
type m and n4
10,20
TYPE B:
0
TYPE CENTERS:
-10,-6,-85
TYPE SCALE:
.06
CHANGE:

volume
VOLUME= 0.400351E 05
CHANGE:

area
A= 0.451534E 04      MARG=      1
A= 0.472393E 04      MARG=      2
A= 0.482979E 04      MARG=      3
A= 0.486251E 04      MARG=      4
A= 0.486251E 04      MARG=      4
CHANGE:
```



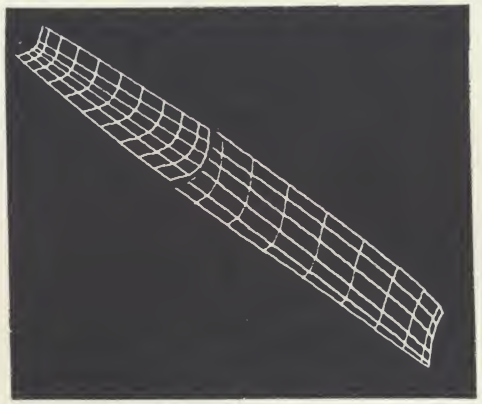
PROFILE



BODY PLAN



HALF-BREADTH



ROTATED VIEW

Fig. 16 Photographs of Destroyer Hull

These pictures were taken from the face of the display scope. The hull shape is modeled by two surface patches photographed separately and pieced together above.

DIMENSIONS

L	369'
B	39'
H	12.5'
C_p	.625
$\triangle$	2750

VI. ECONOMICS

The results of this report demonstrate that a computer-aided system for the preliminary design of ships is technically feasible. In this last section the authors describe the equipment used in this study and examine the economic implications of such a design system.

A. EQUIPMENT

The central item in the equipment needed to operate a time-sharing computer-aided design system is, of course, a high-speed digital computer. For most designers, who will simply be users of a system in a relationship analogous to an individual and the telephone company, the economic questions will be in terms of hourly or monthly rental fees for the time used. Therefore, on the next page an attempt is made to estimate operational costs for preliminary ship design. However, it might be useful for large companies and government agencies or simply for general interest to mention briefly some representative capital costs for such a computer.

Initial costs vary widely and are determined to a large extent by the amount of high-speed core memory, the amount of bulk store (discs and drums), the number of time-sharing consoles, etc. It is estimated that the hardware portion of the M.I.T. Project MAC Time-Shared IBM 7094 Computer would cost over four million dollars to duplicate. It is also true that a system somewhat less extensive than M.I.T.'s installation could be used appropriately at a cost of about three million dollars. Another possibility is that a different, smaller capacity computer, for example, a PDP-6 from Digital Equipment Corporation, might be used, requiring an investment of about one million dollars. These costs are quite approximate.

When a computer and a time-sharing system are available, a design console, consisting of teletypewriter and display system, completes the necessary package of equipment.

Several types of teletypewriters are available, and both the Teletype, Model 35 KRS and the IBM 1050 were used in this thesis. Present monthly rental fees run about $75 for each Teletype and $140 for each IBM 1050, plus telephone line charges.

The two-terminal display system (the ESL Console)* used in this report was designed and constructed by the M.I.T. Electronic Systems Laboratory, as part of an Air Force supported project on Computer-Aided Design.** A Type 330 Incremental Display constructed by the Digital Equipment Corporation (DEC) to M.I.T. specifications is a part of the system. The ESL Console contains two display scopes: one master scope for primary viewing and one slave scope for secondary purposes, e.g., photographs. Initial cost of this system was in the neighborhood of $60,000. At the present time a number of commercial display units are available at a cost of $50,000 - $100,000, but none have exactly the same features as the system used in this report.

Figure 17 on the next page shows photographs of the design console and its two main components used in the development and operation of the authors' computer-aided design process.

B. OPERATIONAL COSTS

With such questions as: 1) obtaining the use of a main computer, 2) development costs of time-sharing, and 3) development costs of CAD still very much unsettled, it would be impossible to evaluate the overall economic picture presented by the design system developed here. However, the operational costs incurred in this as a working design system can be estimated quite closely.

For instance, for the destroyer example in the previous Section, the computer time used for each of the major calculations and operations (when done in the given order) is listed below:

Item	Computer Time Used in Seconds
1. Δ solution	12.3
2. speed-power curve	0.6
3. weight estimate	1.6
4. sectional area curve	14.3
5. hull display	27.3
6. surface area	28.8
7. volume	4.3
8. midship coefficient	3.5
9. centers of buoyancy	25.1
Total	137.8 seconds

* Stotz, R., "Man-Machine Console Facilities for Computer-Aided Design," Proceedings of the SJCC, Detroit, May, 1963.

**Contract AF-33(657)-10954

a) Display Scope

(Rotation input device is at lower left)

b) Teletype

c) Complete Design Console

Fig. 17 Design Console and Components

Since rental fees for the computer can range from \$300 to \$700 per hour, an average figure of \$450/hour or \$7.50 per minute might be used as an estimate. At this rate, that portion of the feasibility study listed above for DD 692 would cost \$17.20 in computer time plus two man-hour's worth of work by the naval architect. If and when this project is extended to the point where a complete feasibility study is accomplished, as described in Fig. 2, it might be reasonable to assume that the total computer time needed might be six times that for the DD 692 -- a total of \$103.20. Including arrangement of spaces, etc., to arrive at a satisfactory GM for stability, designer's time might be four hours. Thus, the total operational costs are summarized below, assuming \$10,000/year for a designer and 100 percent overhead costs:

Item	Time	Rate	Cost
Computer	13.8 minutes	\$7.50 per minute	\$103.00
Designer	4 hours	\$5.00 per hour	20.00
Overhead	4 hours	100 percent	20.00
Total operational cost			\$143.00

As a rough estimate for comparison, it might take one man-week (\$400 including overhead) to accomplish the same study manually, assuming that this were a reasonably standard hull shape and class of ship.

While all of the foregoing figures are the author's estimates and may be subject to various degrees of controversy, the ability of the computer to produce at least 60,000 operations (multiplications, divisions, etc.) per second in a time-sharing mode at a cost of \$0.125 per second is well established.

C. EVENTUAL IMPLICATIONS

Whether in actual practice each computer-aided feasibility study will be much cheaper and faster than each present manual study remains to be seen. One alternative possibility is that each feasibility study done with the aid of a computer will examine and present a whole range of solutions -- rather than just one solution -- to the problems posed by the Ship Characteristics Board in the same time and at roughly the same cost as a much less extensive manual study.

The idea that the designer can (in a CAD system) explore a much wider range of answers to the decision-makers' questions may be an appealing one, particularly because of the vagueness and changeability of the ship's missions at the inception of the design. No one can assess the value of having examined five to ten times as many feasible solutions from the infinite set available in each problem, but the implication certainly is that the results will be better, more economical ships.

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APPENDIX A

LIST OF PROGRAMS

The following programs were developed in the course of the work reported here. Since the details of these programs depend so heavily on the particular characteristics of the Project MAC Time-Sharing System and of the ESL Display Console, program listings contained in the original thesis have been omitted from this memorandum. For those interrested in the listings, copies of the thesis can be obtained from the M. I. T. Library.

WTPOWR	GEN
READIN	TANGT
SACURV	FLOAT
SURFAC	IVORY

APPENDIX B

1. DERIVATION OF EQUATIONS FOR SACURV

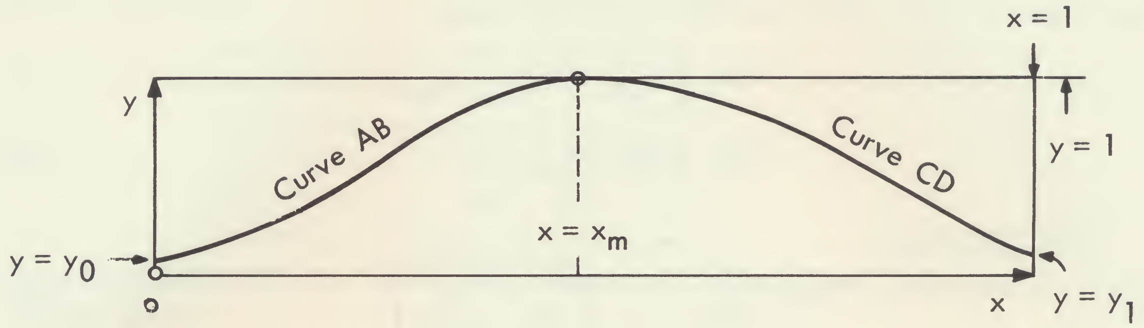

Fig. 18 Sectional Area Curve

For curve AB

$$x_{ab} = A_1u^3 + A_2u^2 + A_3u + A_4 \tag{1}$$

$$y_{ab} = B_1u^3 + B_2u^2 + B_3u + B_4 \tag{2}$$

For curve CD

$$x_{cd} = C_1u^3 + C_2u^2 + C_3u + C_4 \tag{3}$$

$$y_{cd} = D_1u^3 + D_2u^2 + D_3u + D_4 \tag{4}$$

For curve AB

$u = 0, \; x = 0 \qquad \boxed{A_4 = 0}$

$u = 0, \; y = y_0 \qquad \boxed{B_4 = y_0}$

$u = 1, \; x = x_m, \; y = 1$

$$A_1 + A_2 + A_3 = x_m \tag{5}$$

$$B_1 + B_2 + B_3 = 1 - y_0 \tag{6}$$

$u = 1, \; \frac{dy}{dx} = 0 \quad \frac{\partial y}{\partial u} = 0, \; \frac{\partial x}{\partial u}$ is arbitrary.

calling $\frac{\partial x}{\partial u}$ = xuab,

$$3B_1 + 2B_2 + B_3 = 0 \tag{7}$$

$$3A_1 + 2A_2 + A_3 = xuab \tag{8}$$

Equations 5, 6, 7, and 8 can be combined into:

$$2A_1 + A_2 = xuab - x_m \tag{9}$$

$$2B_1 + B_2 = y_0 - 1 \tag{10}$$

<u>For curve CD</u>

$$u = 0, \quad x = x_m \qquad \boxed{C_4 = x_m} \tag{11}$$

$$u = 0, \quad y = 1 \qquad \boxed{D_4 = 1} \tag{12}$$

$$u = 0, \quad \frac{dy}{dx} = 0 \qquad \frac{\partial y}{\partial u} = 0, \quad \frac{\partial x}{\partial u} \text{ is arbitrary}$$

Calling $\frac{\partial x}{\partial u}$ = xu0,

$$\frac{\partial x}{\partial u} = 3C_1u^2 + 2C_2u + C_3 = xu0$$

and

$$\frac{\partial y}{\partial u} = 3D_1u^2 + 2D_2u + D_3 = 0,$$

but u = 0, so

$$\boxed{C_3 = xu0} \tag{13}$$

and

$$\boxed{D_3 = 0} \tag{14}$$

At $u = 1$, $x = 1$, $y = y_1$

$$C_1 + C_2 + C_3 = 1 - x_m \tag{15}$$

$$D_1 + D_2 + D_3 = y_1 - 1 \tag{16}$$

Also at $u = 1$, $\frac{dy}{dx} = t$. Either $\frac{\partial x}{\partial u}$ or $\frac{\partial y}{\partial u}$ is arbitrary. Making $\frac{\partial x}{\partial u}$ = xu1,

$$3C_1 + 2C_2 + C_3 = xu1 \tag{17}$$

$$3D_1 + 2D_2 + D_3 = t(xu1) \tag{18}$$

However, from (13), $C_3 = xu0$:

$$C_1 + C_2 = 1 - x_m - xu0 \tag{19}$$

$$3C_1 + 2C_2 = xu1 - xu0 \tag{20}$$

From these, we find

$$\boxed{C_2 = 3 - xu1 - 2xu0 - 3x_m} \tag{21}$$

and

$$\boxed{C_1 = 1 - x_m - xu0 - C_2} \tag{22}$$

which is the most efficient form for computer calculation. Similarly, from Eq. 14, $D_3 = 0$:

$$D_1 = D_2 = y_1 - 1 \tag{23}$$

$$3D_1 + 2D_2 = t(xu1) \tag{24}$$

Thus, we find

$$\boxed{D_2 = 3y_1 - 3 - t(xu1)} \tag{25}$$

and

$$\boxed{D_1 = y_1 - 1 - D_2} \tag{26}$$

As shown above, $A_4, B_4, C_1 \ldots C_4$, and $D_1 \ldots D_4$ are obtainable directly from input information. However, two more equations (in addition to Eq. 9 and Eq. 10 above) are needed to solve for $A_1 \ldots A_3$, and $B_1 \ldots B_3$. These equations are supplied from C_p and LCB restrictions.

For the prismatic coefficient,

$$\int_0^{x_m} AB(x)\,dx + \int_{x_m}^{1} CD(x)\,dx = C_p \tag{27}$$

In parametric terms, this becomes

$$\int_0^{x_m} y_{ab}(u)\,dx_{ab} + \int_{x_m}^{1} y_{cd}(u)\,dx_{cd} = C_p \tag{28}$$

But

$$dx_{ab} = (3A_1u^2 + 2A_2u + A_3)\ du \tag{29}$$

and

$$dx_{cd} = (3C_1u^2 + 2C_2u + C_3)\ du \tag{30}$$

and the limits become u = 0 and u = 1 for both terms. Now, if we call

$$du = y_{ab}(u)\ dx_{ab} \quad \text{and } du = y_{cd}(u)\ dx_{cd},$$

then

$$\begin{aligned} p = {} & (3A_1B_1)u^5 + (3A_1B_2 + 2A_2B_1)u^4 \\ & + (3A_1B_3 + 2A_2B_2 + A_3B_1)u^3 + (3A_1B_4 + 2A_2B_3 + A_3B_2)u^2 \\ & + (2A_2B_4 + A_3B_3)u + (A_3B_4) \end{aligned} \tag{31}$$

and similarly for q. Then, if we denote $\int_0^1 p\ du$ by P and $\int_0^1 q\ du$ by Q, we have

$$P = C_p - Q \tag{32}$$

and this yields

$$\begin{aligned} & \frac{3A_1B_2 + 2A_2B_1}{5} + \frac{3A_1B_3 + 2A_2B_2 + A_3B_1}{4} + \frac{3A_1B_4 + 2A_2B_3 + A_3B_2}{3} \\ & + \frac{A_1B_1 + 2A_2B_4 + A_3B_3}{2} + A_3B_4 = C_p - \Bigg[\frac{3C_1D_2 + 2C_2D_1}{5} \\ & + \frac{3C_1D_3 + 2C_2D_2 + C_3D_1}{4} + \frac{3C_1D_4 + 2C_2D_3 + C_3D_2}{3} \\ & + \frac{C_1D_1 + 2C_2D_4 + C_3D_3}{2} + C_3D_4\Bigg] . \end{aligned} \tag{33}$$

In the same manner, we can derive the last necessary equation from the LCB condition. In parametric terms,

$$\int p\ x_{ab}(u)\ du + \int q\ x_{cd}(u)\ du = C_p\ x_c \tag{34}$$

where

$$x_c = \text{LCB}.$$

This results in an equation of the form:

$$\frac{3A_1^2 B_2 + 5A_1A_2B_1}{8} + \frac{3A_1^2 B_3 + 5A_1A_2B_2 + 4A_1A_3B_1 + 2A_2^2 B_1}{7}$$

$$+ \frac{3A_1^2 y_0 + 5A_1A_2B_3 + 4A_1A_3B_2 + 3A_2A_3B_1 + 2A_2^2 B_2}{6}$$

$$+ \frac{2A_2^2 B_3 + 5A_1A_2y_0 + 4A_1A_3B_3 + 3A_2A_3B_2 + A_3^2 B_1}{5}$$

$$+ \frac{2A_2^2 y_0 + 4A_1A_3y_0 + 3A_2A_3B_3 + A_3^2 B_2}{4}$$

$$+ \frac{A_1^2 B_1 + 3A_2A_3y_0 + A_3^2 B_3}{3} + \frac{A_3^2 y_0}{2} = (C_p)(x_c)$$

$$- \text{ similar CD terms} \qquad (35)$$

Equations 5, 6, 7, 8, 33, and 35 must be combined to produce a solution of A and B coefficients. Because the last two equations are so complex, a trial-and-error technique was adopted whereby different values A_1 and B_1 are tried until all equations are met within specified tolerances. For all practical purposes the solution set for both A_1 and B_1 lies within a range of values between +2.0 and -2.0.

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Univac, Division Sperry Rand Corporation
Attn: Mr. R.W. Bemer
351 Park Avenue South
New York 10, New York

University of California
Department of Engineering
Attn: Dr. Allen B. Rosenstein
405 Hilgard Avenue
Los Angeles 24, California

The Warner and Swasey Research Center
Attn: Mr. S.F. Winchell,
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28999 Aurora Road
Cleveland 39, Ohio

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Attn: NASA Representative (SAK/DL)
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